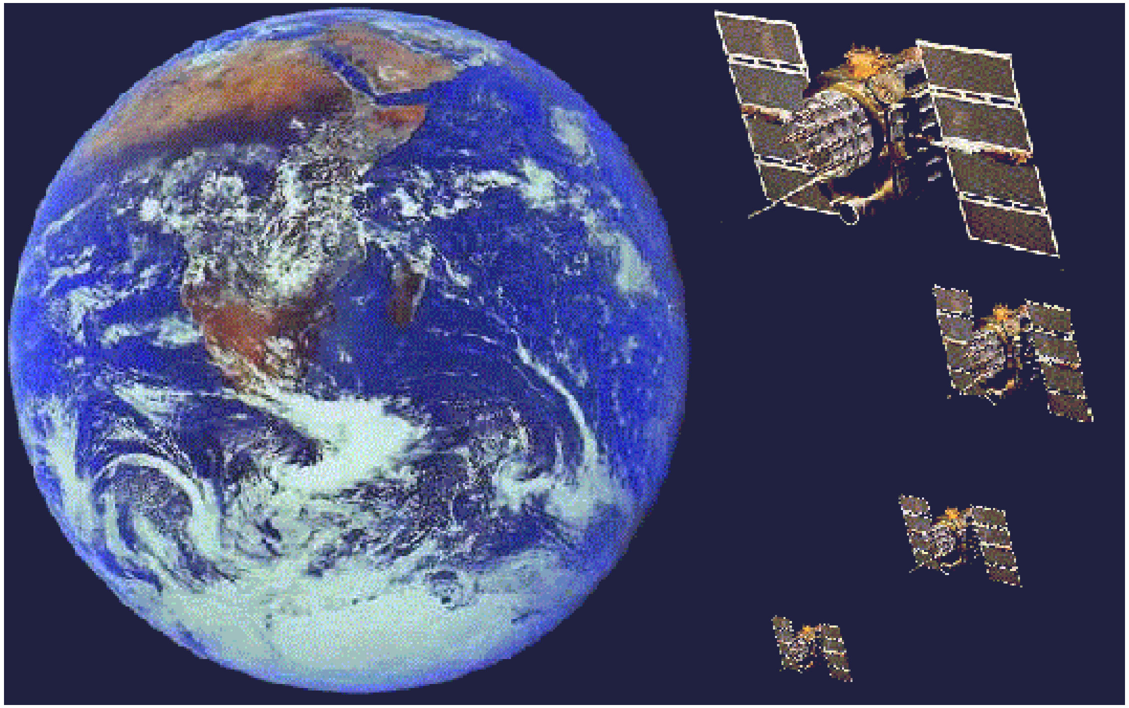
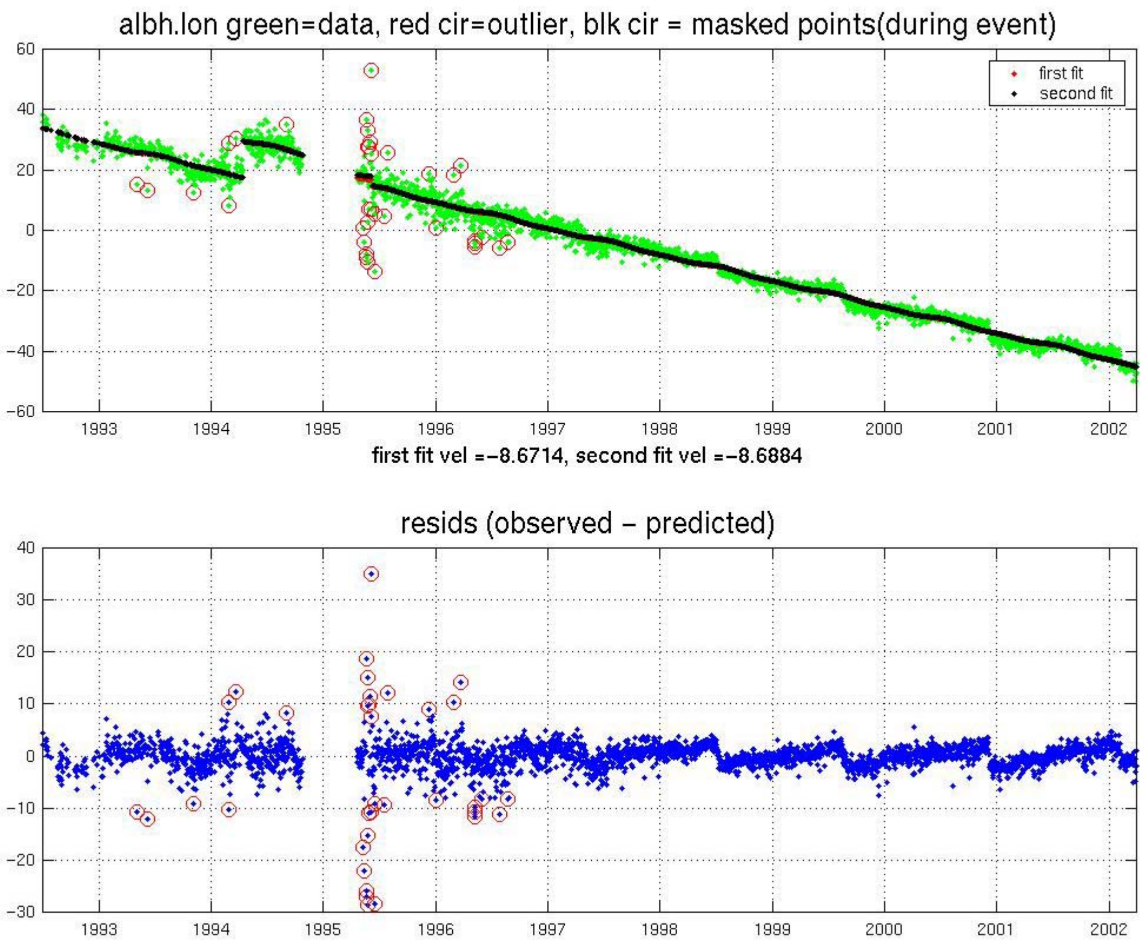
GPS

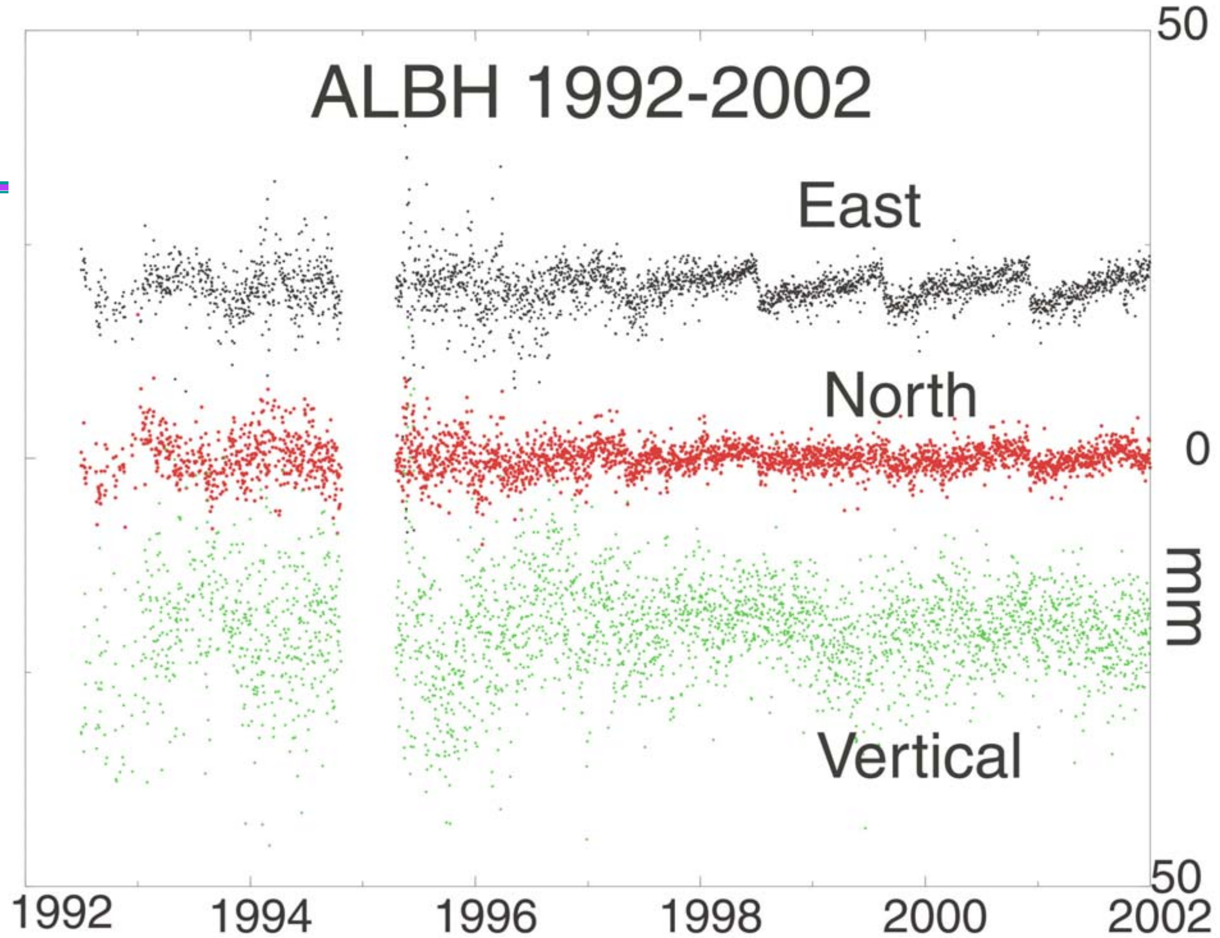
Frank Webb
Jet Propulsion Laboratory (JPL)



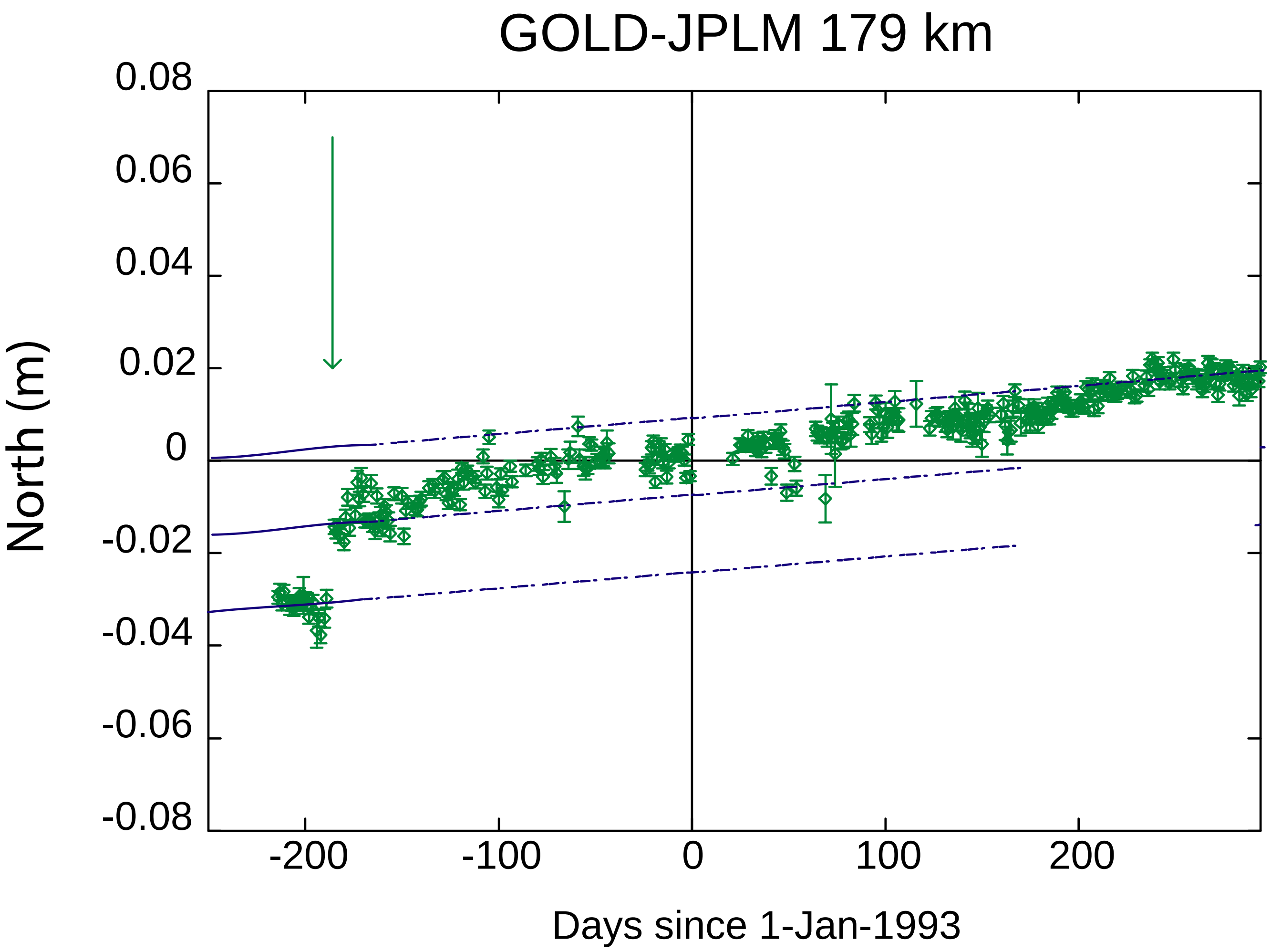
"I just don't understand how you guys do it?", A JPL Colleague

How do you get from radio waves from satellites to this?



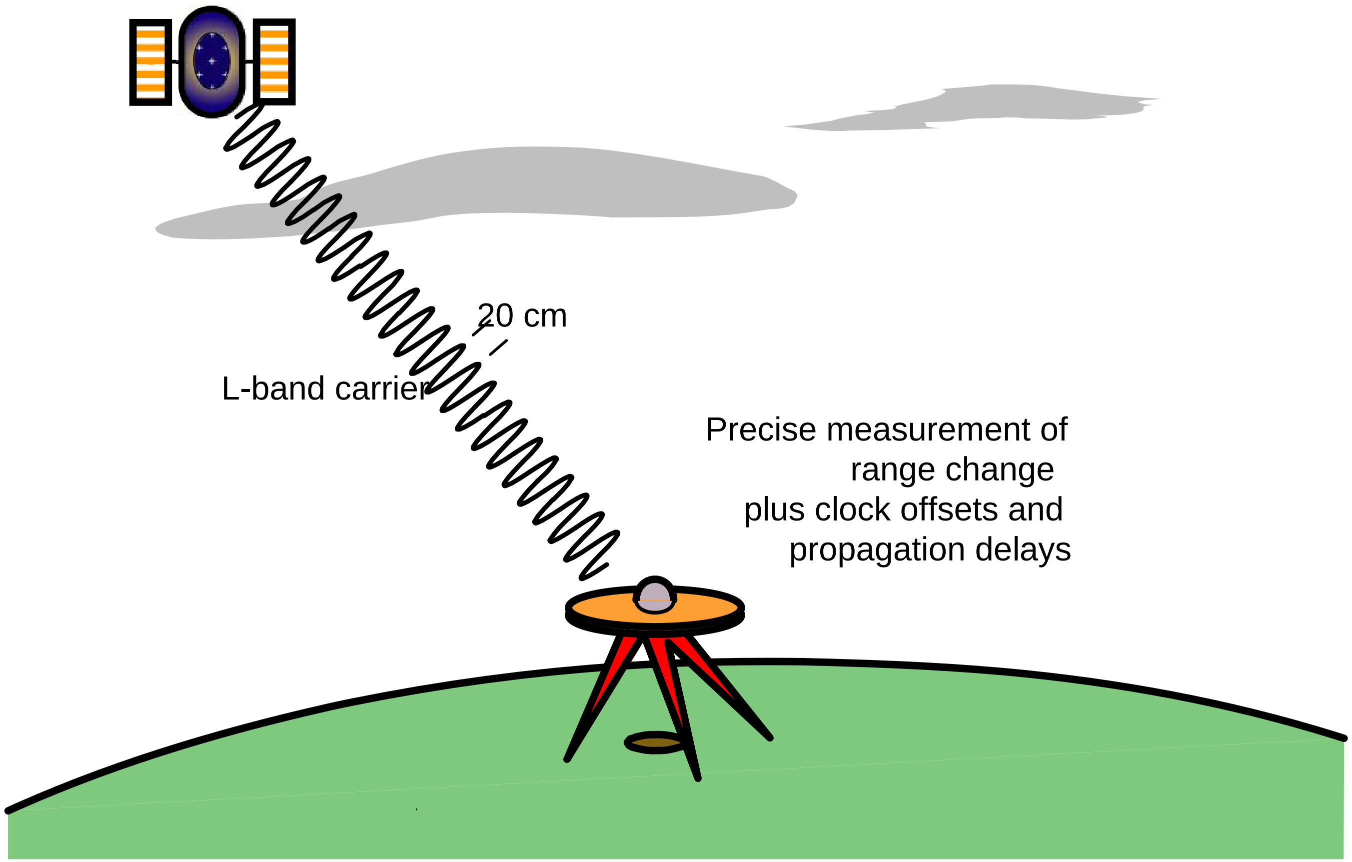


GPS resolution is not sufficient to determine sub-cm vertical motion


GOLD-JPLM 179 km
North (m)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-200
-100
0
100
200
Days since 1-Jan-1993

Carrier Phase

Millimeter precision measurement of GPS carrier phase



Pseudorange

Pseudorange Measurement with square wave ranging code

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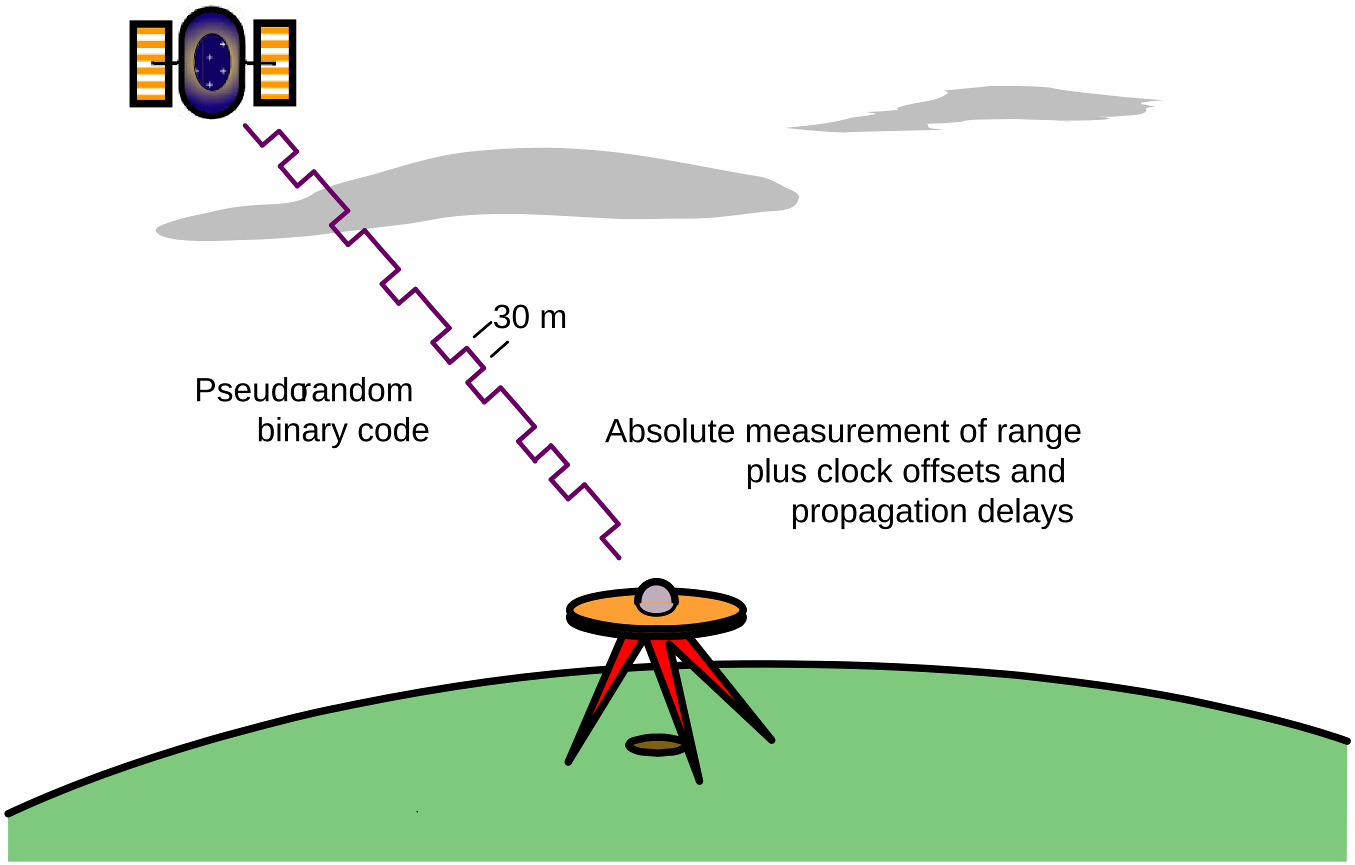


Observation Equations

- The observations, L and P, are modeled as

$$L = \rho + c\,(dt - dT) + \lambda b - d_{ion} + d_{trop}$$

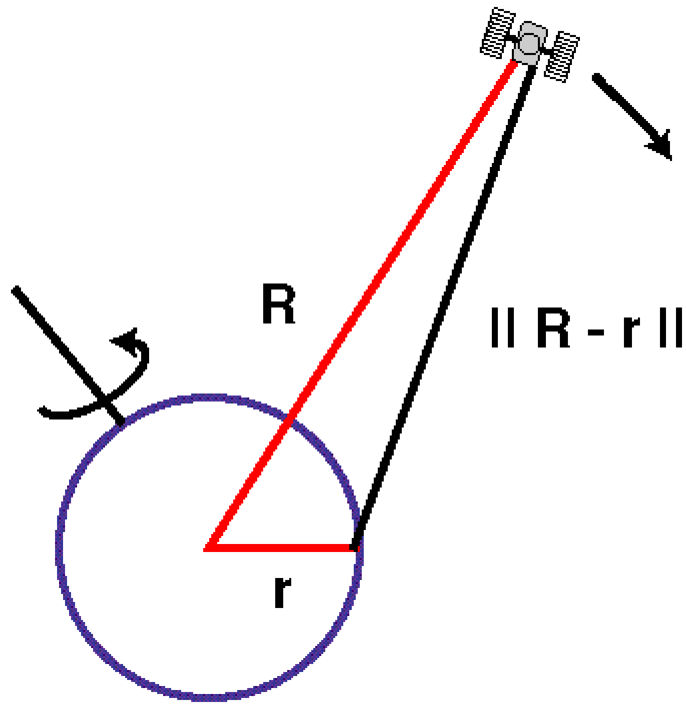
$$P = \rho + c\,(dt - dT) + d_{ion} + d_{trop}$$

- where the geometric range to the satellite is given by

$$\rho = \| R - r \|$$

- This range is a function of time as the satellites orbit the earth and are affected by solar radiation and gravity; the earth rotates and precesses; and the surface of the earth deforms due to ocean loading, solid earth tides, seasonal loading, atmospheric loading.

- The goal is to model the GPS observations and to estimate corrections to that model.



Questions

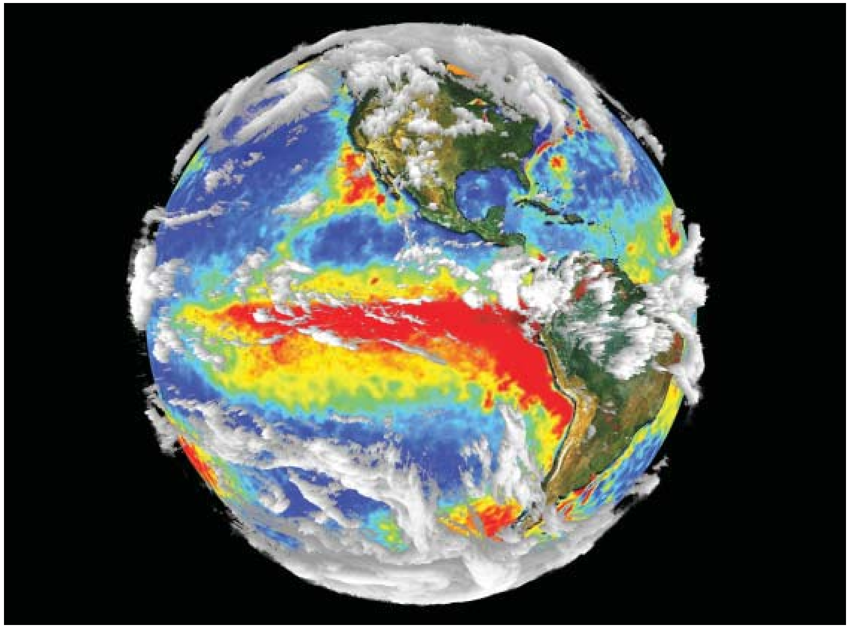
- What is GPS?
- How does GPS work?
- What are the key issues?
- What is the resolving power of GPS “observations”?
- How does one use it?
- What questions should I ask about a GPS “result”?

Roadmap

- Background and definitions
  - What is geodesy?
  - How is it traditionally used in Earth science?
  - What is space geodesy?
  - What is the state of the art?
  - What do I mean by gravity, J2, load moments, reference frames?

- Solid-fluid interactions
  - What are they?
  - How can space geodesy observe those?
  - What are we learning?

- Future
  - What are the opportunities?
  - What are the challenges?



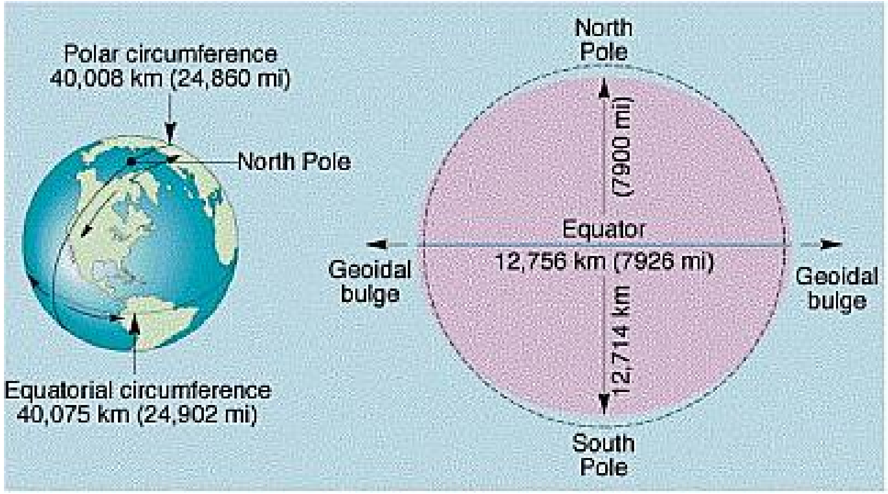
What is Geodesy?

- Some common definitions:

  “The science of determining the size and shape of the Earth and the precise location of points on its surface.” US Geoloical Survey

- *“Geodesy is the branch of science that deals with such topics as determining positions and areas over large parts of the Earth, the shape and size of the Earth, and the [spatial] variations in the Earth's gravitational and magnetic fields.” Mathematica.*

These and, temporal changes in the location of points on the surface of the Earth and changes in the size, shape, and mass distribution of the Earth.



Traditional Geodesy

- Primarily concerned with practical issues of positioning and shape
  - Where are the land boundaries?
  - Where is the coastline for navigation?

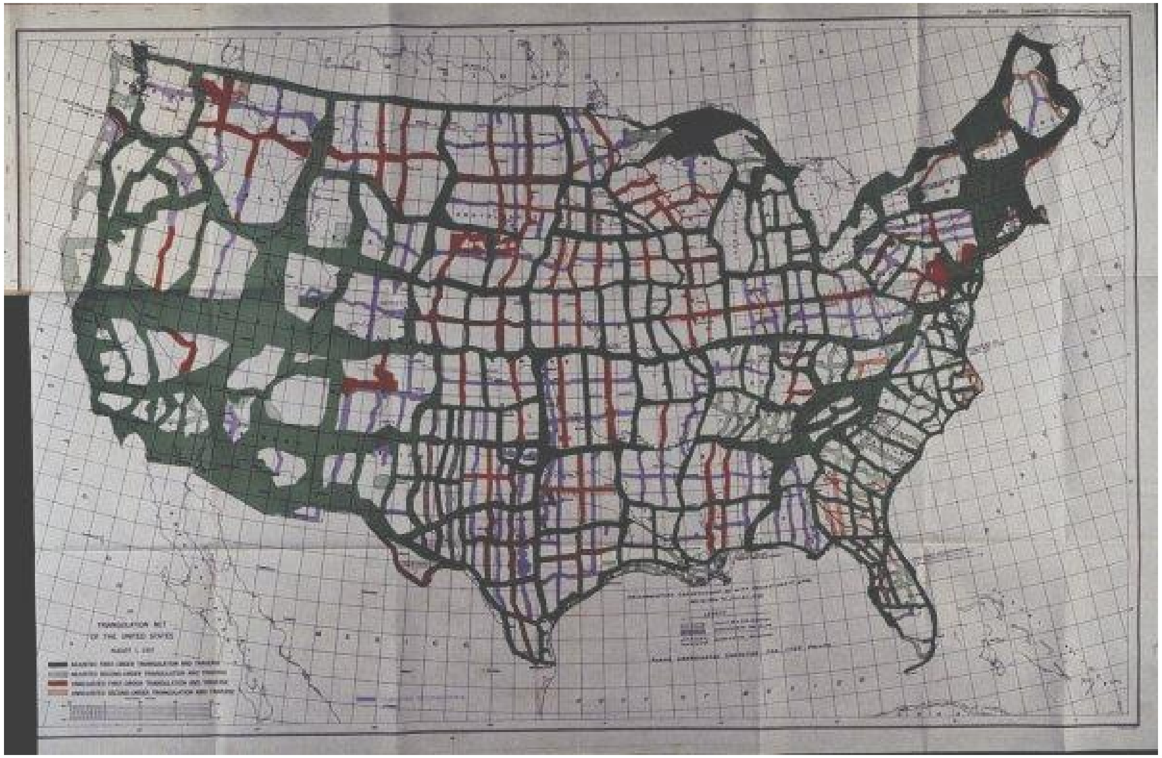
- Ground based and labor intensive techniques

- Precision about 1-10 ppm of the distance obsderved

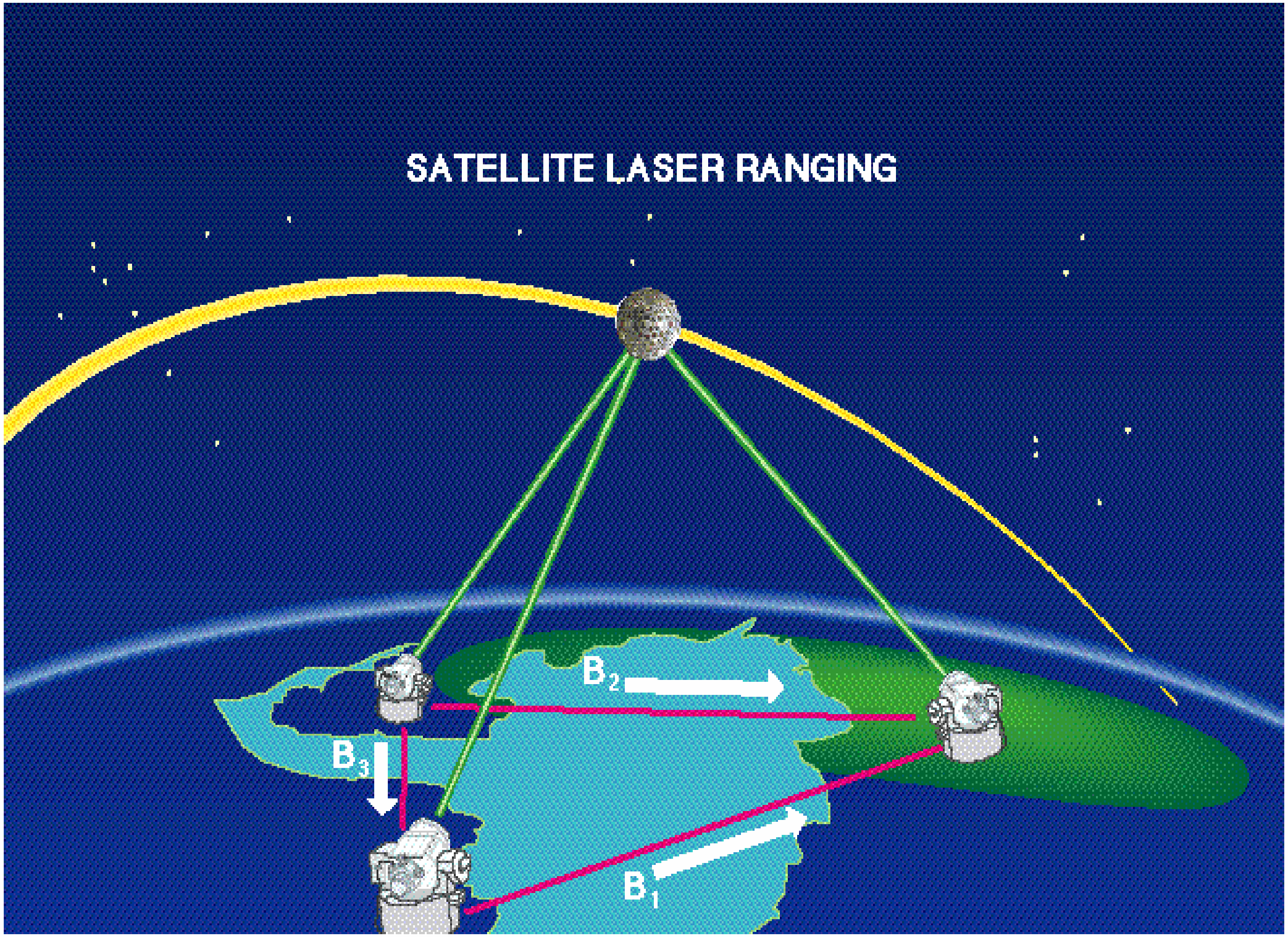
  .1 – 1 m over 100km

Traditional Geodesy

- Local or continental scale measurements
- Long, arduous measurement campaigns lasting days, years, decades
- No time dependent measurements
- Hand computations

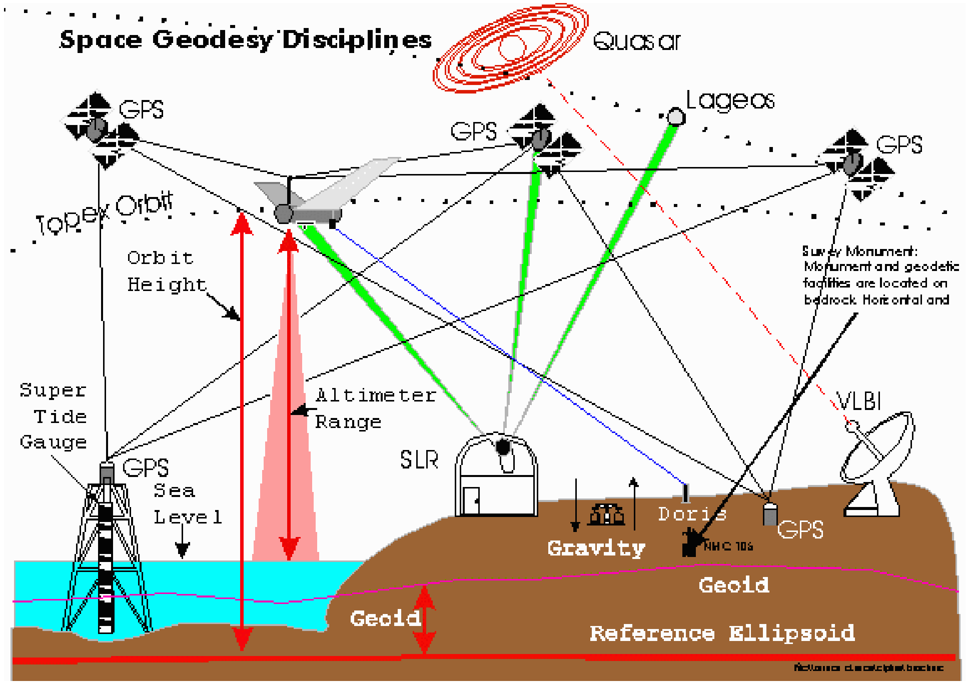


Space geodesy



What is “Space Geodesy”?

- Global scale scientific issues of positioning, shape and mass distribution and redistribution.
- Terrestrial and space components (sources and orbiters)
- Technology intensive systems
- Precision about 1 ppb of the distance
  - Diameter of Earth to 1 cm
- Used for understanding time dependent changes in the Earth system



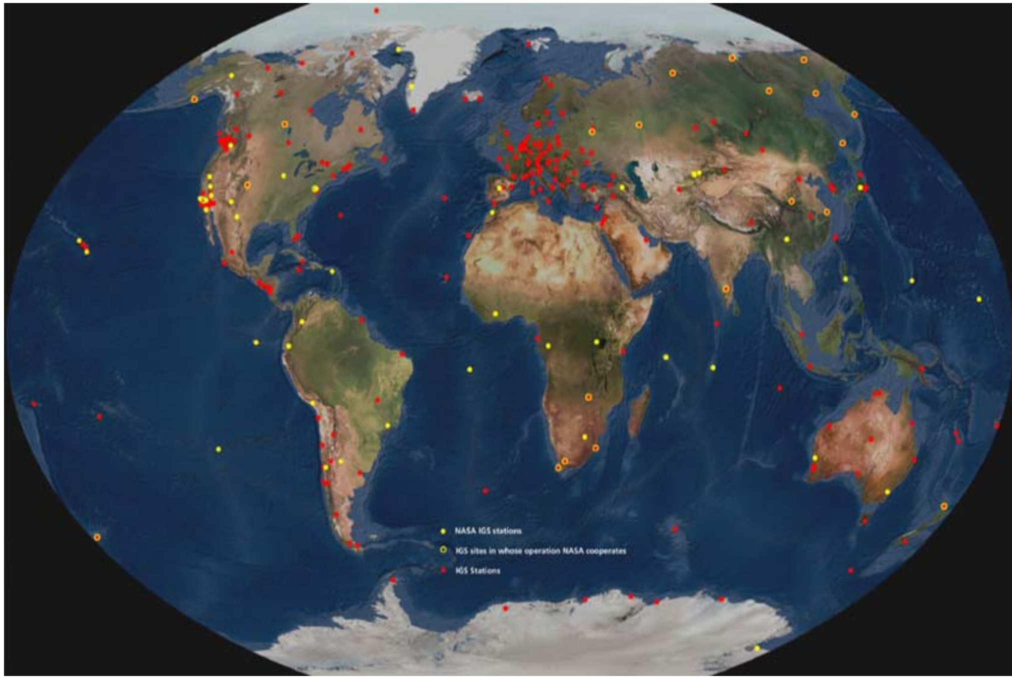
Any sufficiently advanced technology is indistinguishable from magic. ***[Arthur C. Clarke](#)***

What does space geodesy do?

- Directly measure Earth science parameters
  - e. g., volcanic and tectonic deformations, gravity field, Earth rotation
- Provide the accurate and stable terrestrial reference frame (TRF) for the interpretation of satellite observations
  - e. g., altimetry
- Precise determination of the orbits of satellites
  - GRACE, TOPEX, Jason, LAGEOS, and many others
- Provide critical information for accurate deep space navigation
- Determine gravity field of the Earth

Global Geodesy with GPS

The Global Positioning System (GPS) is a constellation of 28 satellites; a global tracking network of a few hundred stations; many technologist and scientist around the world.

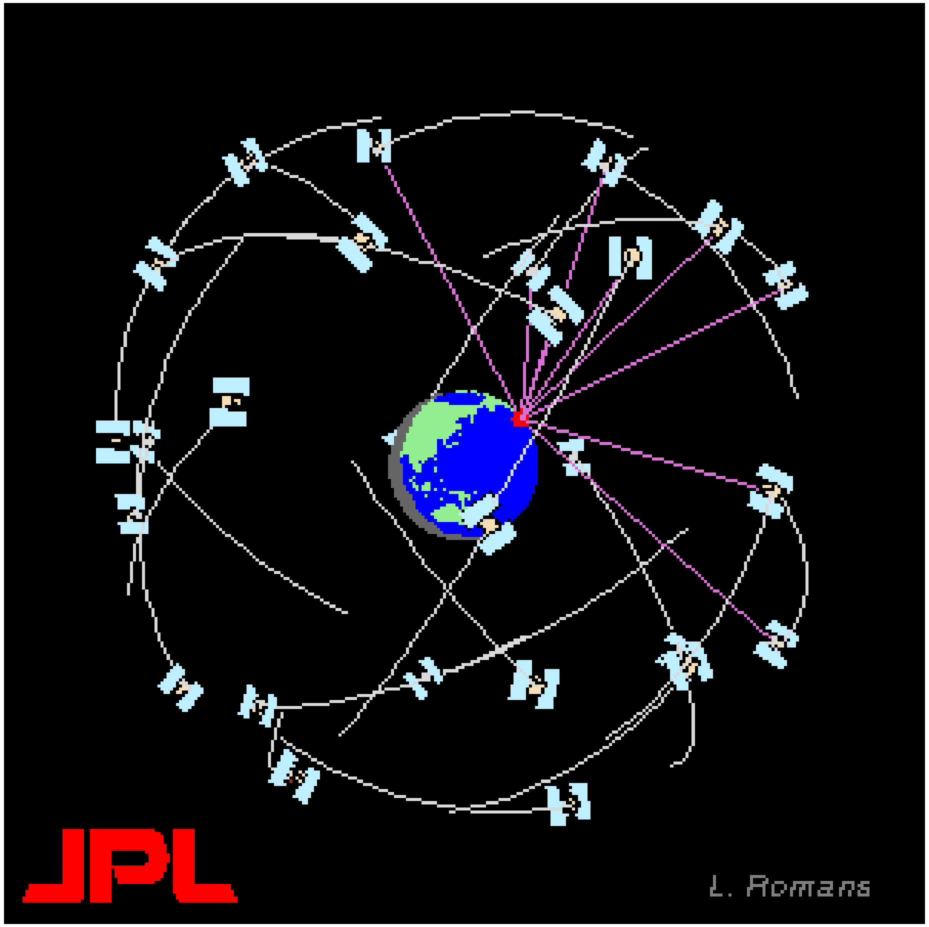


GPS is the state of the art for high precision global positioning:

1-3 mm horizontal and 5-8 mm vertical positioning. 1-2 mm/yr rates

GPS constellation

- Each GPS satellite is in a 26,000 km orbit
- Each satellite has its own response to the non gravitational forces such as solar pressure and commanded maneuvers
- Position in the orbit is known to about 2 cm
- Civilian and other uses require only 1-10 meter orbit knowledge



Solid-fluid interactions - What are they?

- The Earth is a dynamic system

  - Actively moving tectonic plates

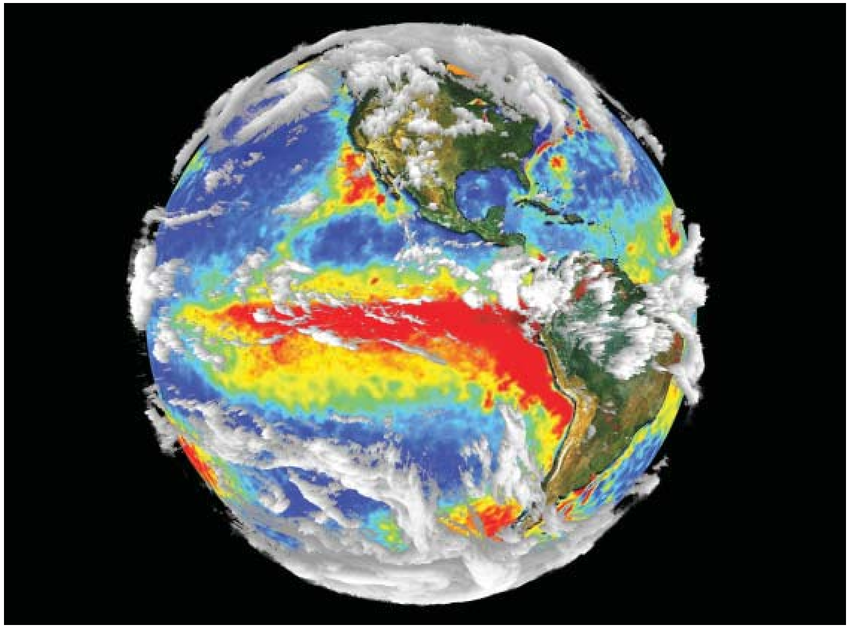
  - Thermally convecting mantle

  - Rebounding crust from glacial loading

  - Fluid core

  - Continually changing global distribution of water (ice, snow, ground water)

  - Global atmospheric and oceanic circulation



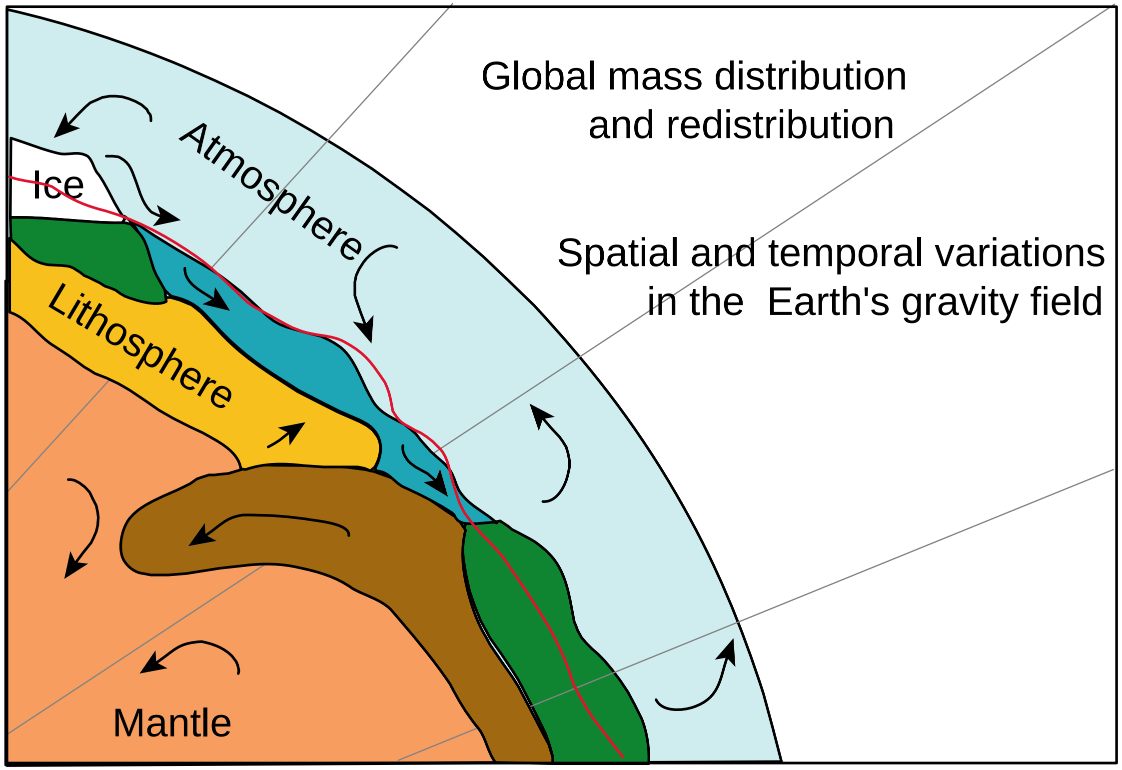
Solid-fluid interactions – What are the effects?

These dynamics result in the redistribution of mass over the Earth's surface causing:

- Changes the location of center of mass of the Earth system

- Changes the shape of gravity field

- Causes surface deformation from redistribution of loads



Cross section of Earth System. Arrows indicate mass transport

How can space geodesy observe those effects?

- Changes in mass distribution of the Earth system

  - Satellite tracking

- Changes in shape of the gravity field

  - Satellite tracking
  - Sea surface altimetry

- Surface deformations from redistribution of loads

  - Precisely position points on the Earth's surface

Redistribution of water on Earth

- How much deformation are we talking about from water moving around on Earth?

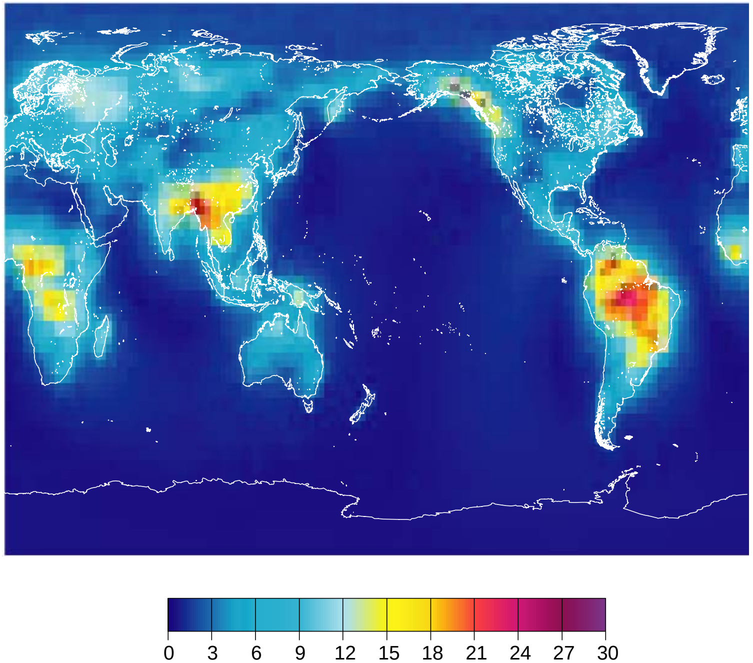
- How big is this mass load on the surface of the Earth?

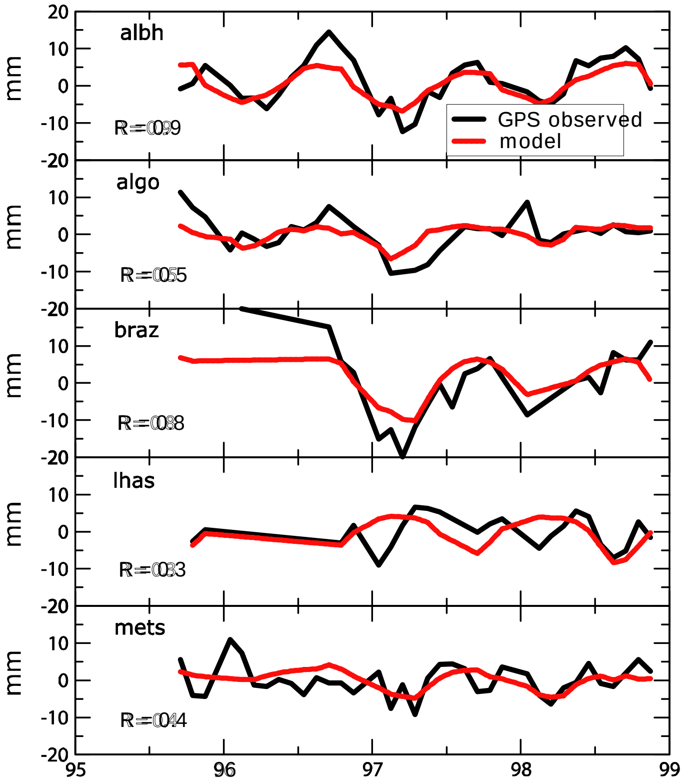
- It needs to be mm level for surface deformations to be observable

How much deformation does water cause?

- Calculate storage of water in snowpack, soil, and groundwater
- Model elastic response of the Earth to surface loads
- Predict vertical motions of the surface
- Compare with GPS based vertical displacements

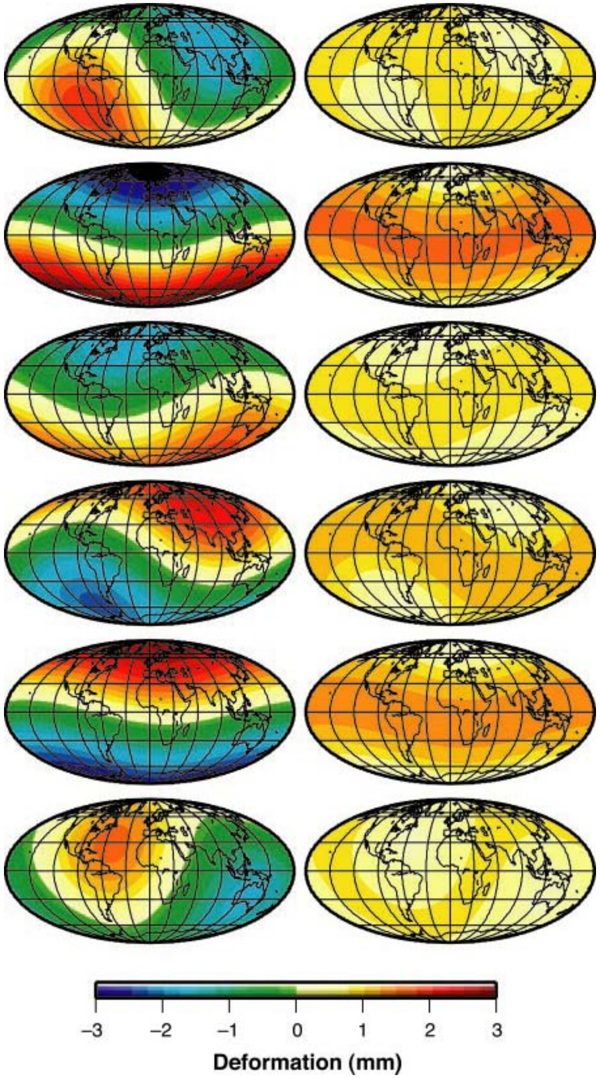
VERTICAL DISPLACEMENT RANGE
caused by total stored water/snow
Maximum - Minimum (1994-98)





Global mode of deformation

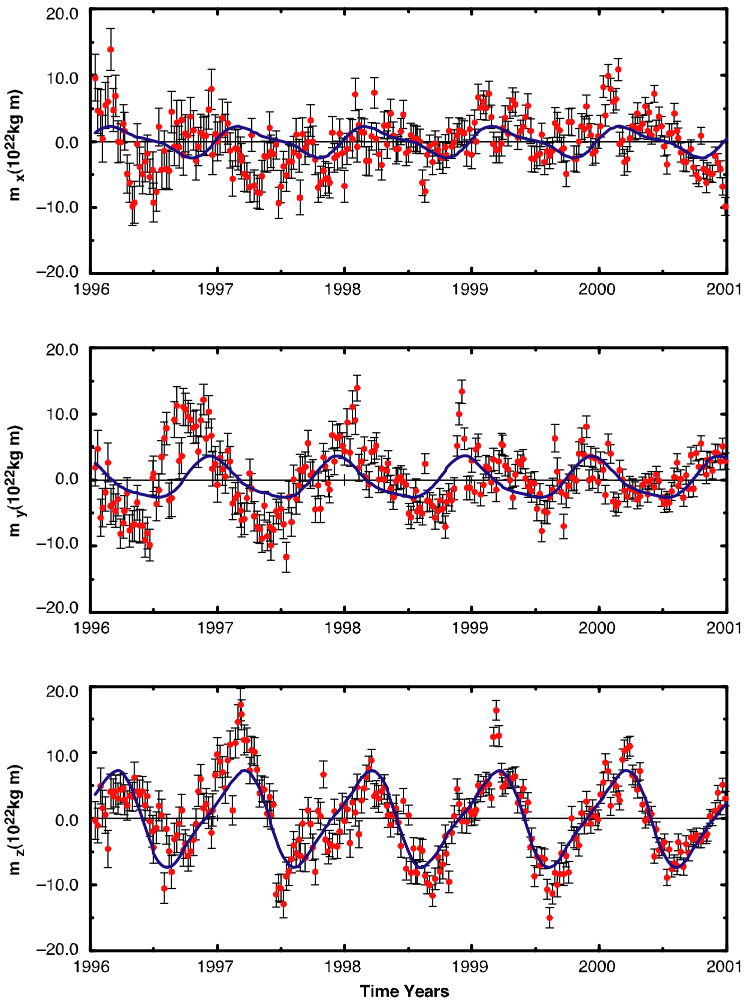
- An elastic response of Earth to a change in the “load moment”.
- Known seasonal exchange of water and air between the Northern and Southern hemispheres is sufficient to force this first order deformation
- Deformation is a compression of one hemisphere centered on the load and expansion of the opposite hemisphere



Vector components of the load moment

- Analysis of GPS data from global distribution of stations (Red dots)

- Empirical model (Black line)



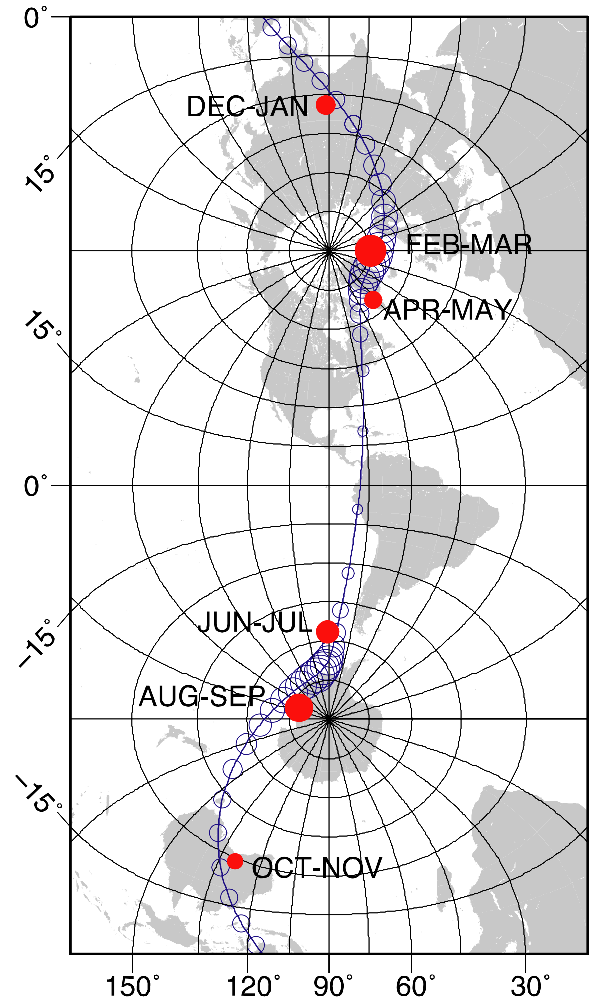
Trajectory of the load moment

- 2 monthly average over 5 years
  - Red dots are observed
  - Blue circles are empirical model

- May be aliasing effects due to non-uniform distribution of GPS stations

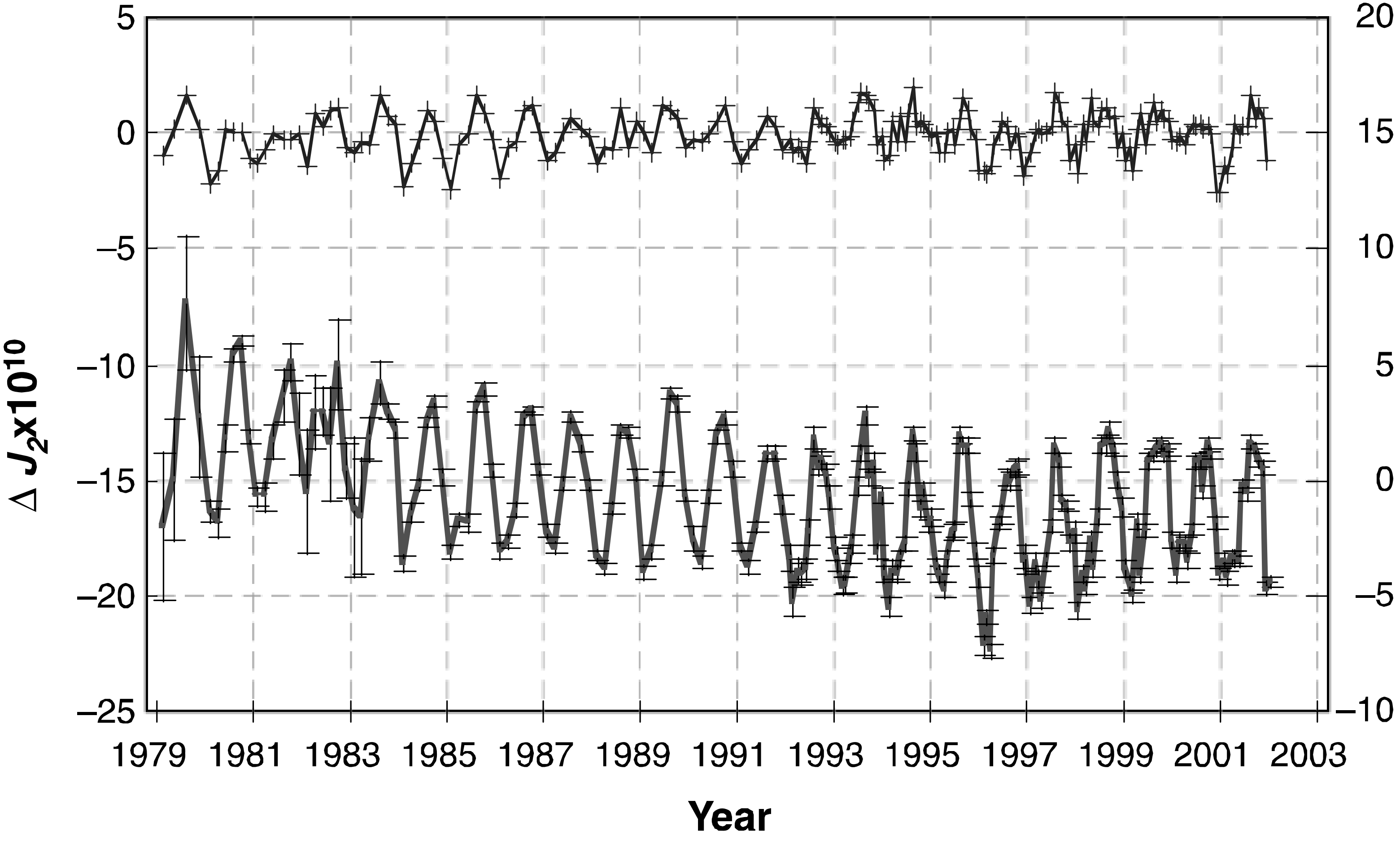
- Monitoring could enable global characterization of the hydrologic cycle.

- First order, global effect



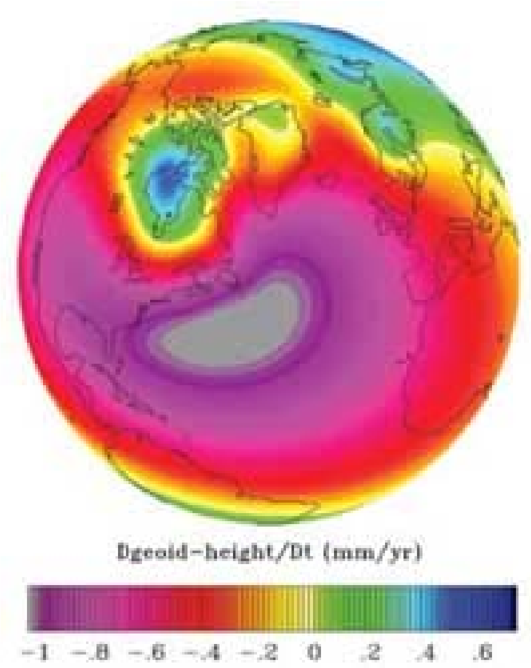
Can get J2 from satellite tracking

- J2 (dynamic oblateness) from SLR (bottom plot)
- Atmospheric contribution (top plot)



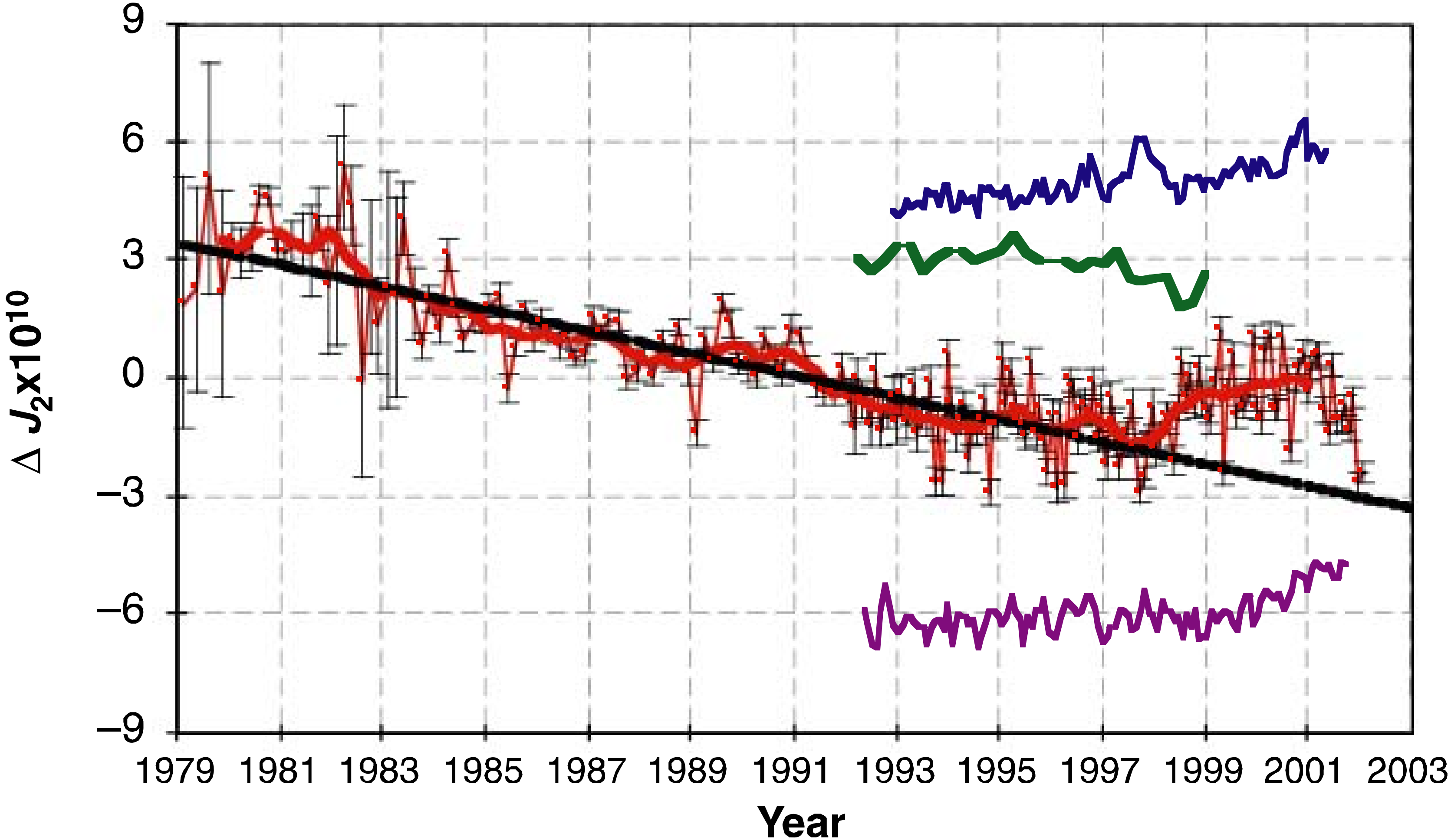
Post Glacial Rebound

- Visco-elastic response (recovery) of the Earth to the removal of the ice sheets from the last ice age.
- Vertical movement of land in many parts of the world.
- Affect relative sea level (RSL) at the coastline in a manner that varies from place to place.
- Confound tide gauge records obtained from coastal sites complicating efforts to track the overall change in global sea level.



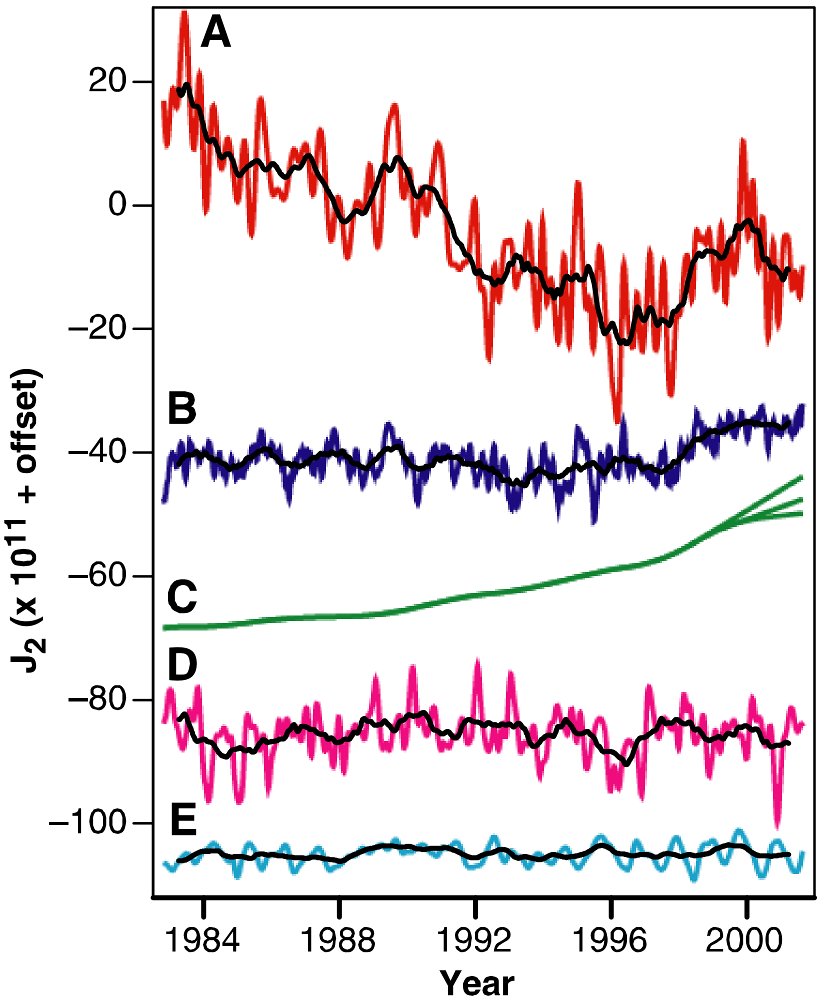
Remove atmospheric model

- Steady decrease in J2 from Post Glacial rebound
- Reverse at time of last El Nino



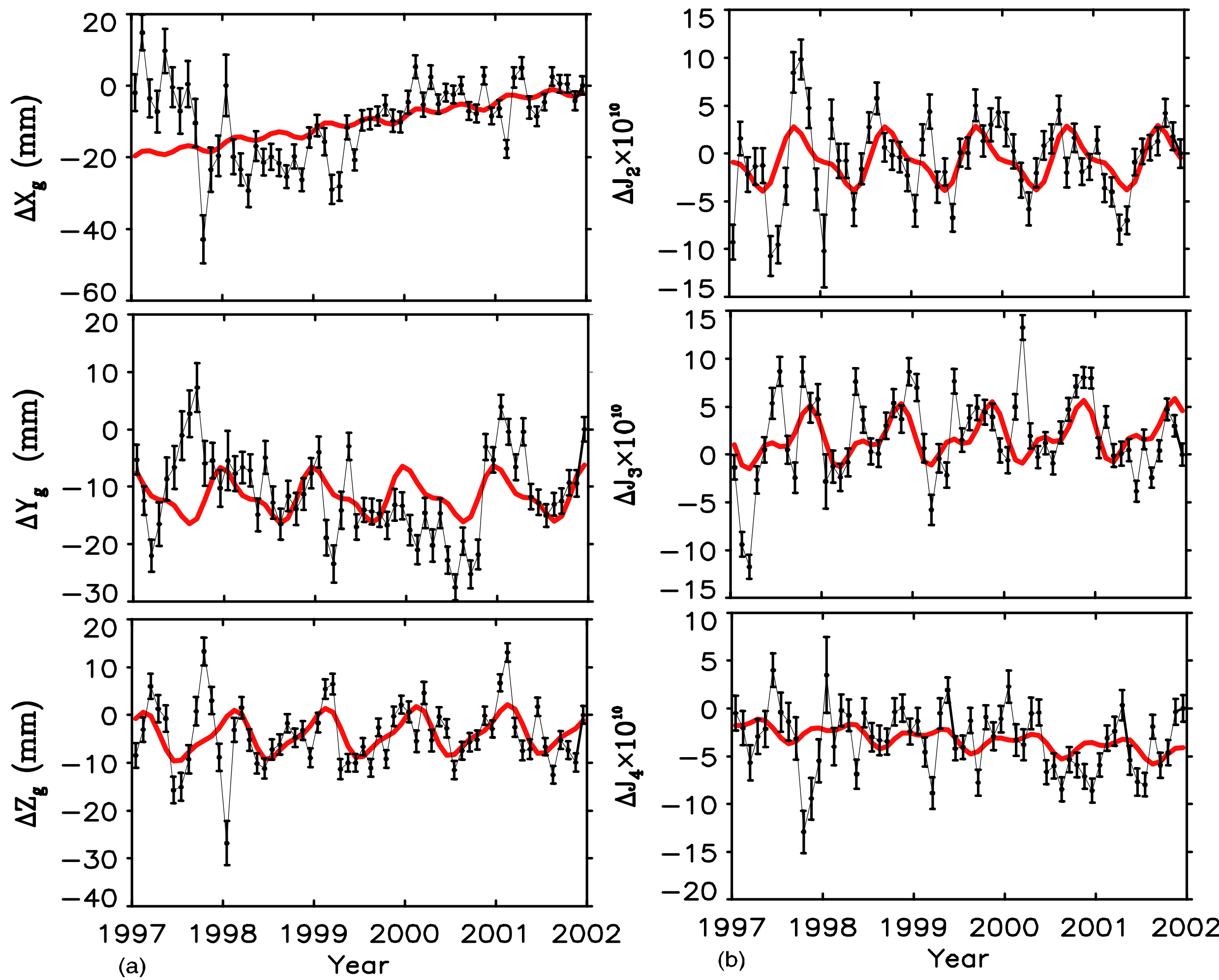
Melting glaciers caused J2 increase?

- J2
- Integrated oceanic effects (ECCO)
- Subpolar glacial effects
- Integrated atmospheric effects
- Integrated groundwater effects



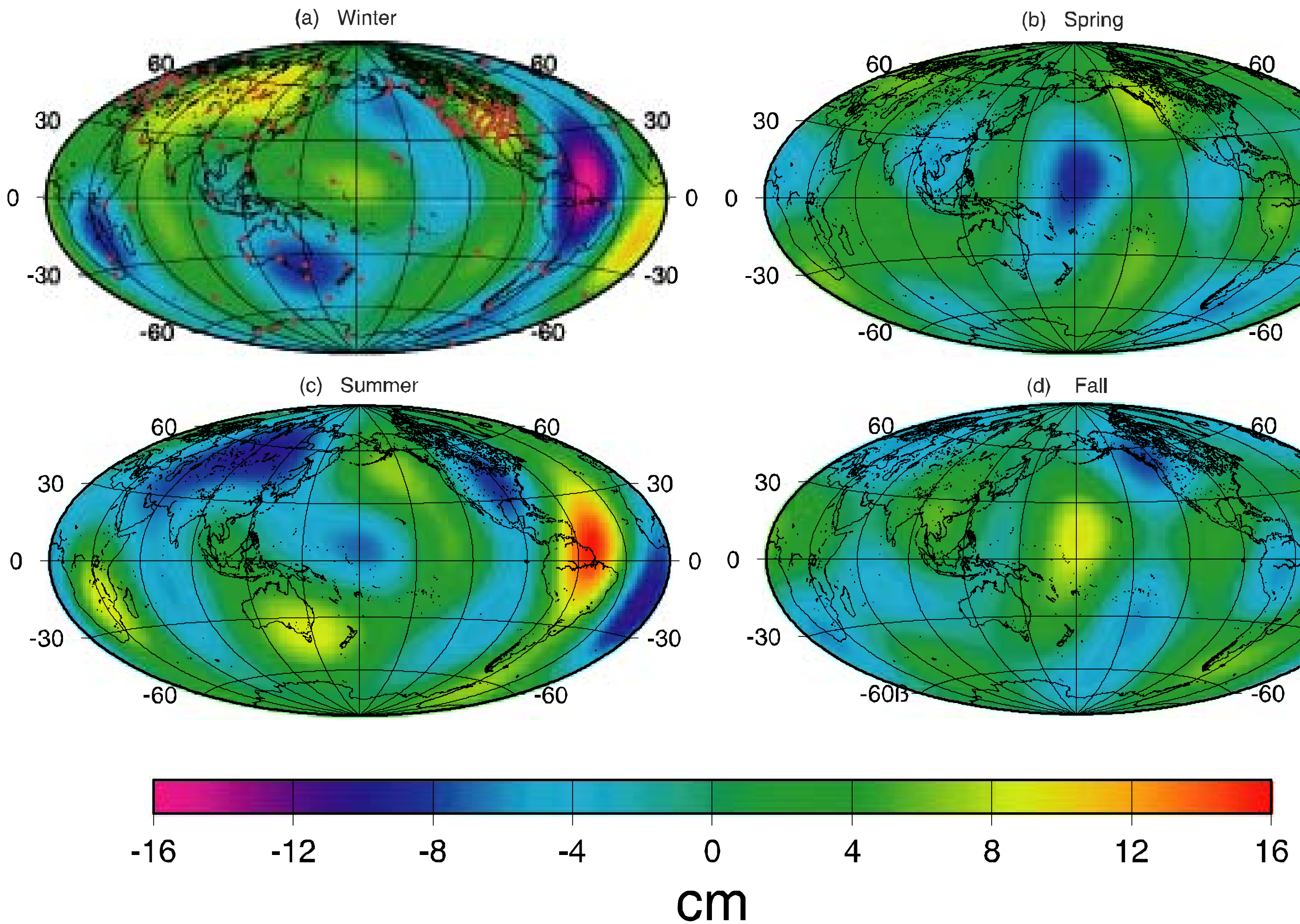
Geocenter and higher order load moments J2, J3, J4

- Motion of globally distributed GPS stations
- Measure how the network moves with respect to center of mass of Earth System (geocenter)
- Compare with imperfect hydrologic and atmospheric models



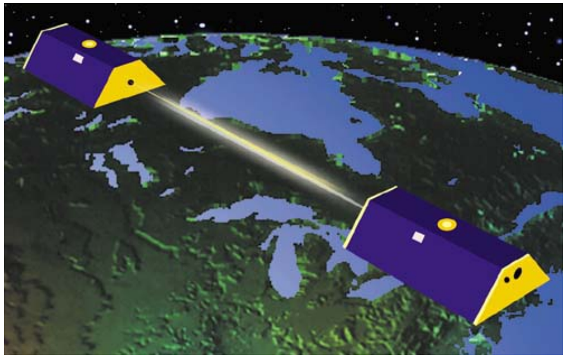
Higher order load moments J2, J3, J4

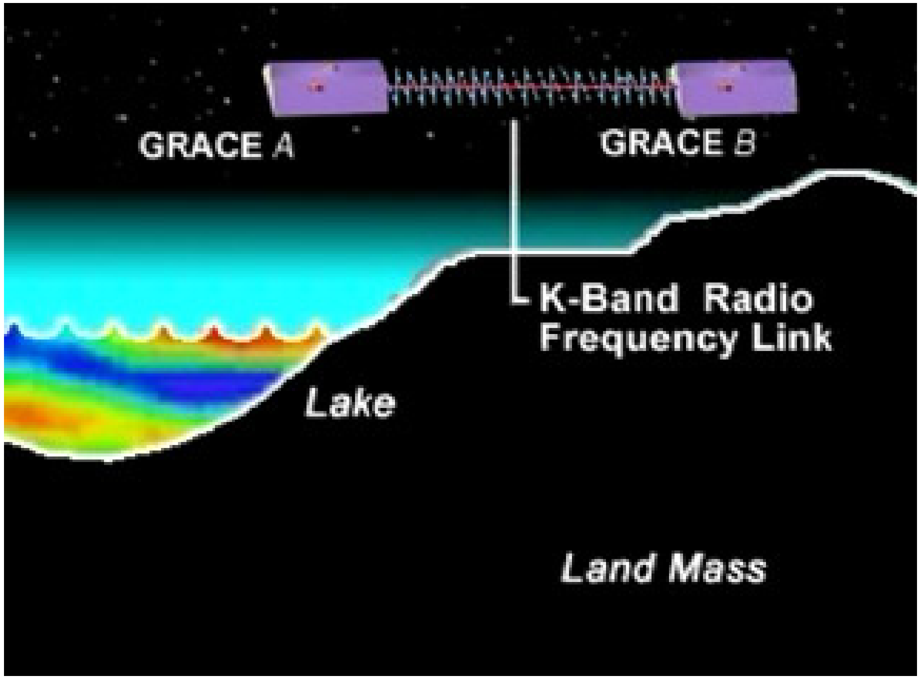
- GPS inverted for large scale annual surface mass variation in water equivalent thickness



Future Opportunities

- Why infer the mass changes from surface deformation when you can measure them?
- Gravity Recovery And Climate Experiment (GRACE)
- Launched in 2002
- NASA, GFZ, UTCSR, JPL





Future Challenges

- Reference Frame Stability

  - New technology will be introduced (GALILEO, GPS3)
  - Instrument aliasing
  - Calibration

- Modeling/assimilation of these diverse data sets

Backup Slides

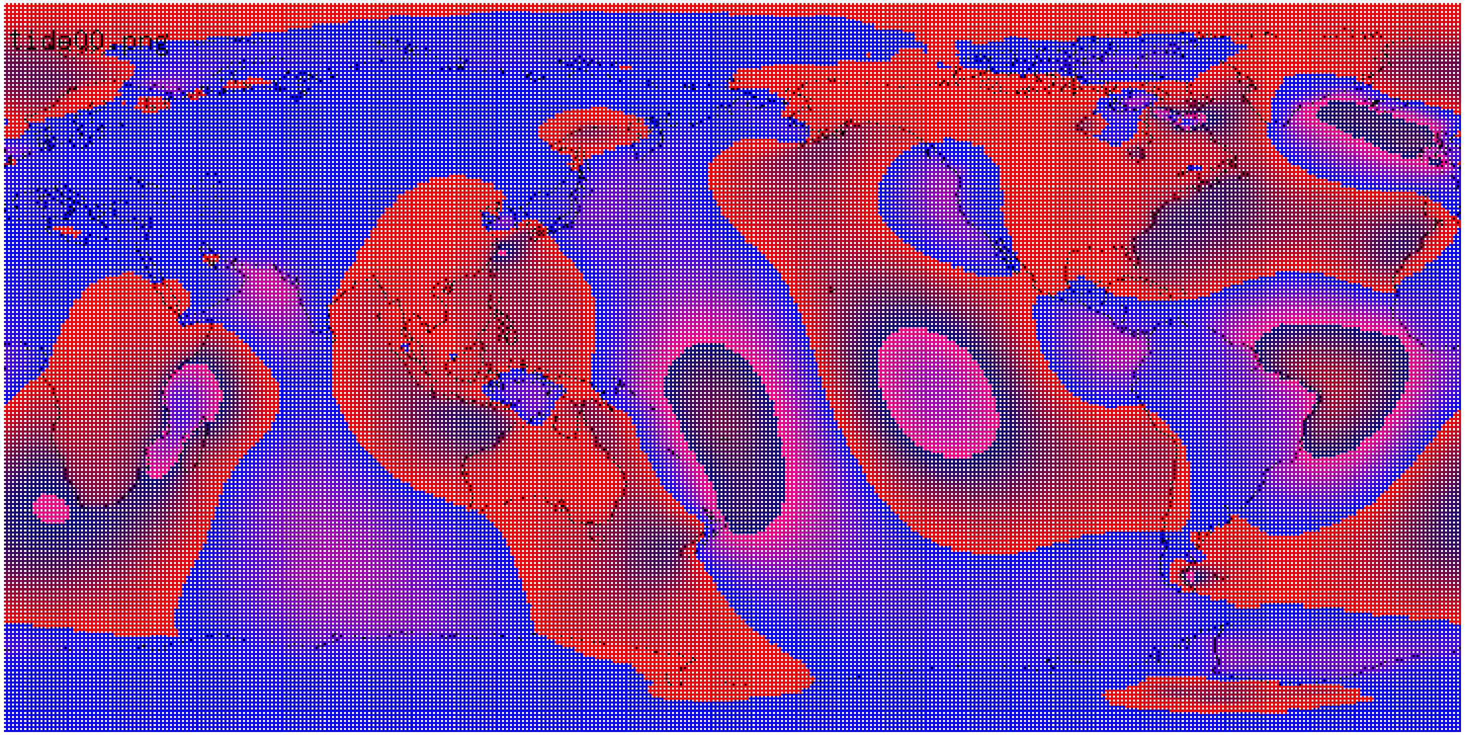
- Backup slides

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them." ***Sir William Bragg***



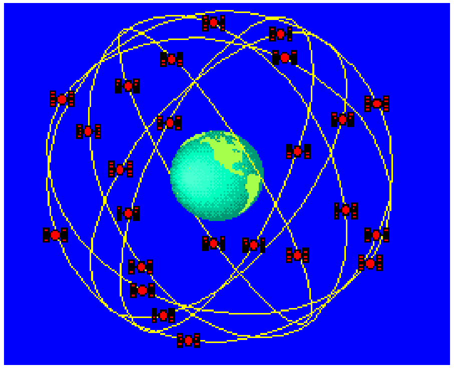

Load deformation example: Ocean loading

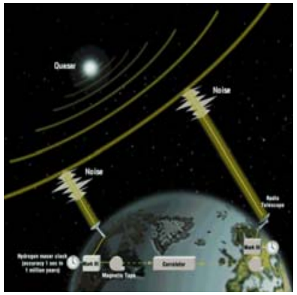
- Ocean tides load the crust
- The twice per day Lunar Tide is the largest component

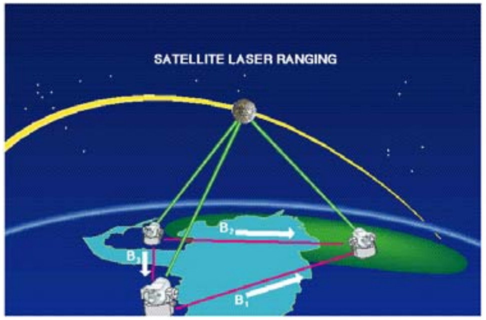


Technology Used

- Global Positioning System (GPS)
  - GPS satellites
  - Ground tracking networks
  - Orbiting receivers
  - Relatively simple analysis systems
- Very Long Baseline Interferometry (VLBI)
  - Quasars
  - Large radio telescopes
  - Relatively intensive analysis systems
- Satellite Laser Ranging (SLR)
  - Earth orbiting satellites
  - Optical telescopes
  - Relatively simple analysis systems





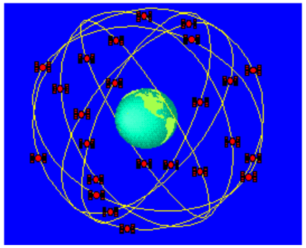


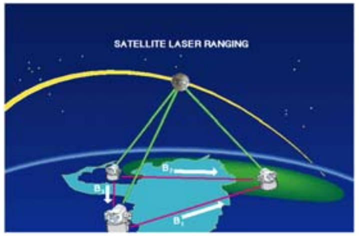
How do these systems interact?

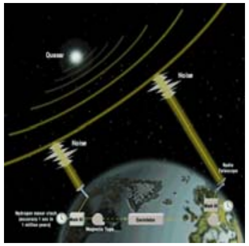
- The Terrestrial Reference Frame (TRF) is an accurate, stable set of positions and velocities.

- The TRF provides the stable coordinate system that allows us to link measurements over space and time.

- The geodetic networks provide data for determination of the TRF as well as direct science observations.







Why do we have three techniques?

- High precision geodesy is very challenging
  - Accuracy of 1 part per billion
- Fundamentally different observations with unique capabilities
- Together provide cross validation and increased accuracy

Technique Signal Source Obs. Type	VLBI Microwave Quasars Time difference	SLR Optical Satellite Two-way range	GPS Microwave Satellites Range change
Celestial Frame UT1	**Yes**	No	No
Scale	**Yes**	**Yes**	Yes
Geocenter	No	**Yes**	Yes
Geographic Density	No	No	**Yes**
Real-time	Yes	No	**Yes**
Decadal Stability	**Yes**	**Yes**	Yes

What are the products?

- TRF: 3-D station positions and temporal evolution
- Earth rotation
- Static and temporal variations in Earth’s gravity field
- Time transfer
- Raw data for other science users
- Precise orbits
- Atmospheric and ionospheric parameters

Who are the users of the data?

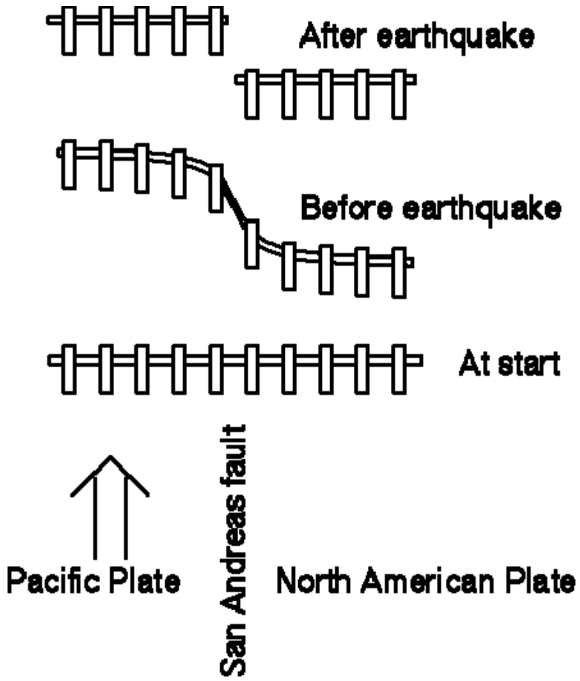
- NASA and non-NASA Flight Missions
- NSF Polar Programs
- USGS National Earthquake Hazards Reduction Program
- DoD
- Land Surveyors
- NOAA/NGS
- ...

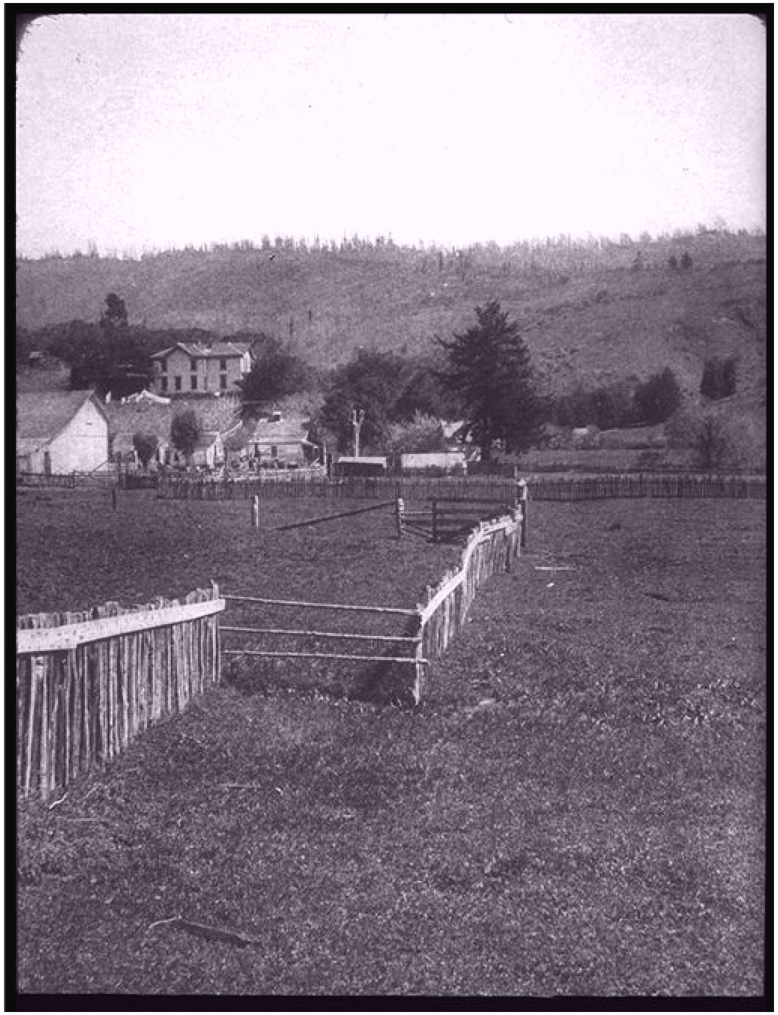
Solid Earth Science Applications

- How much and how does the Earth move before, during and after earthquakes and volcanic eruptions?
- October 28, 1891, M8.0 Nobi Japan earthquake.

Solid Earth Science Applications

- Following 1906 San Francisco earthquake, resurvey of 1878 survey of California coast from 1923-1929.





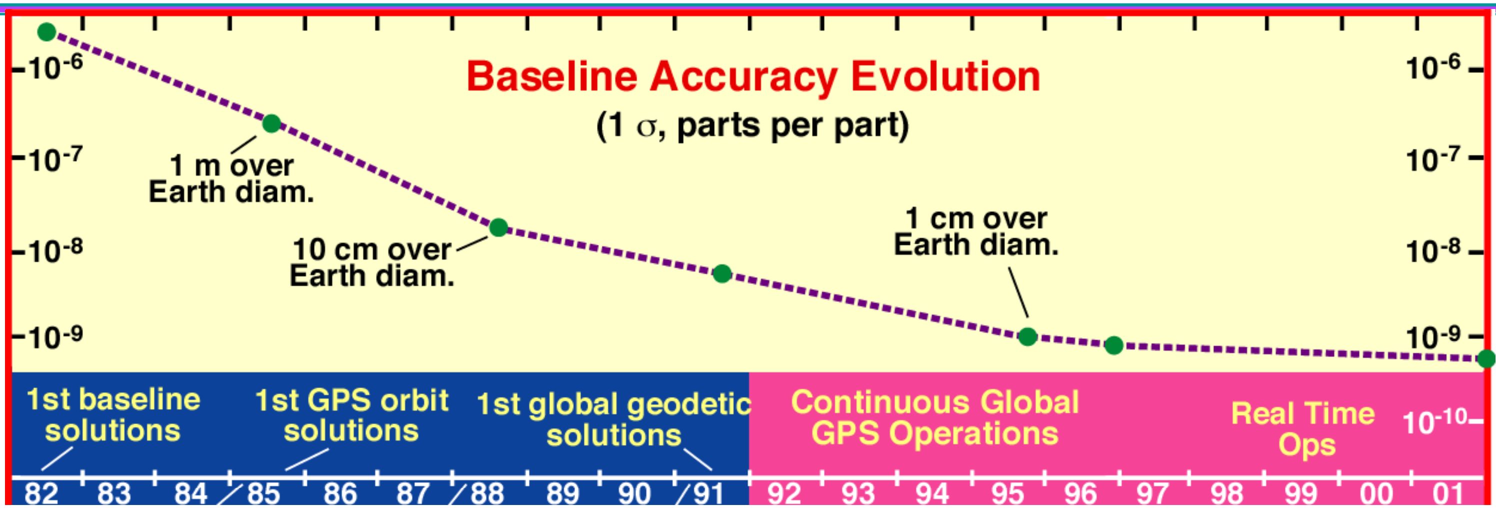
What are the geodetic services?

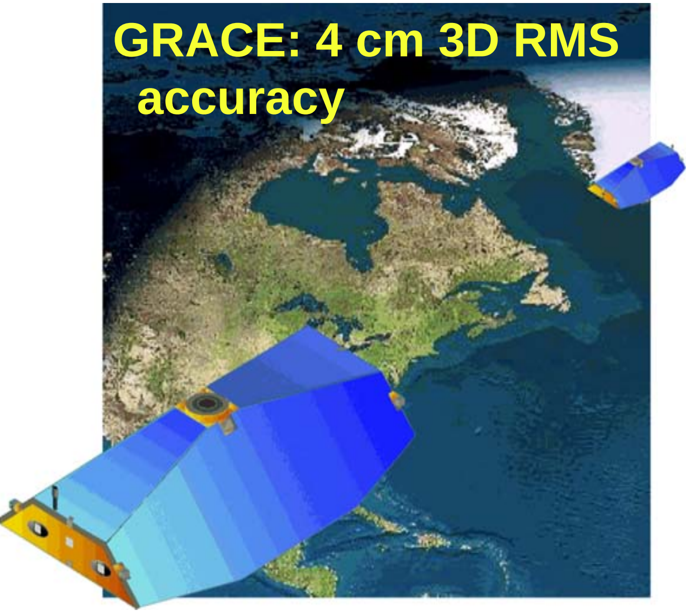
- Parts of the International Association of Geodesy (IAG)
- An example of Community Management Model
  - Develop standards
  - Self regulating
  - Performance monitoring
  - Define and deliver products
- 200+ Organizations in 80+ countries
- NASA actively participates in the services
  - International GPS Service (IGS)
  - International Laser Ranging Service (ILRS)
  - International VLBI Service (IVS)
- Services respond to NASA's program needs

Where are the geodetic networks going?

- Real-time access
- Higher temporal resolution
- Improved accuracy
- Improved global distribution
- Increased efficiency

GPS: Providing Universal Access to the TRF





Diverse benefits to NASA and beyond:

- Solid Earth science (NASA, NSF, USGS)
- Climate science (NASA, NSF, NOAA, USGS)
- National security (DoD)
- Space weather (NASA, USAF, NOAA)
- Flight projects
  - POD and timing (TOPEX, Jason, GRACE,...)

GPS: The Critical Components

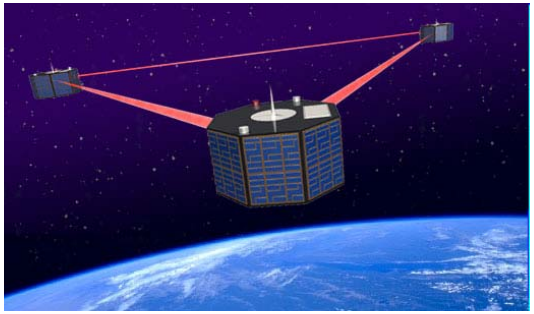
- The global ground network
  - Must provide continuous, stable, and improving realization of the TRF
  - International leadership and collaborations through the IGS
    - Leverage NASA's data to get much more
  - Perpetual challenge for maintenance and upgrade
    - Changing constellation (New GPS frequencies, GPS III, Galileo)
    - Real-time Internet (RTNT)
  - Direct science instruments

- Flight receivers
  - Positioning, orbit determination, and time transfer
    - Continue to advance the state of the art
    - Adapt to new signals
  - Bona fide remote sensing science instruments
    - Unrivaled capability for atmospheric sensing and altimetry

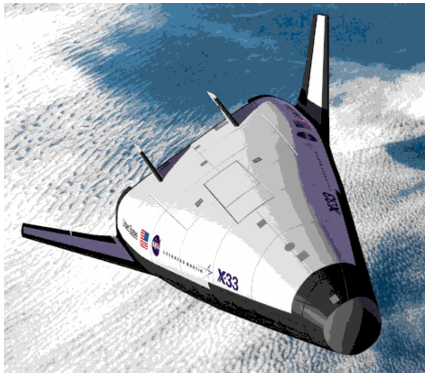
- Analysis, science
  - Physical models
  - POD and positioning accuracy in real time and in post processing
  - Remote science applications: occultations, altimetry, scaterometry

Special Value to NASA and Society

Autonomous operations in Earth orbit to enable smart sensor webs and reduce operational costs and communications bandwidth
- **Prototype GDGPS flight receiver being developed**
- **Precise time transfer for interferometric SAR**

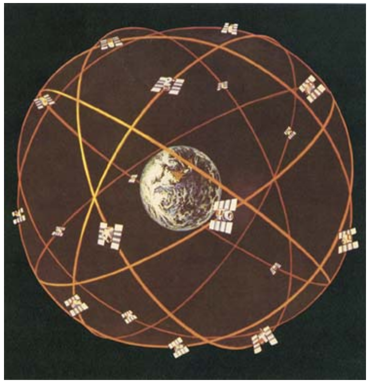


Safe operations for NASA missions
- **RLV navigation payload based on GDGPS**



Timely monitoring and response to natural hazards
- **NRT sea surface height**

Aviation safety and efficiency
- **Dryden plans to offer GDGPS services on all platforms**

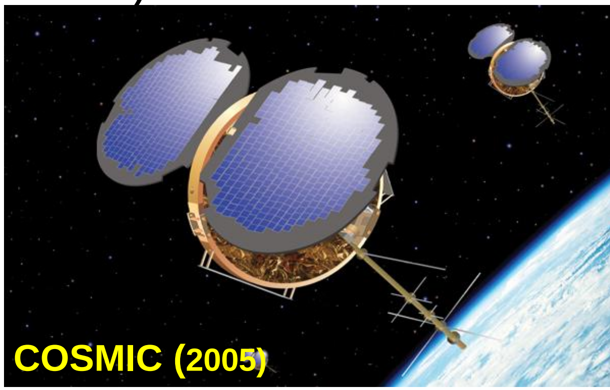


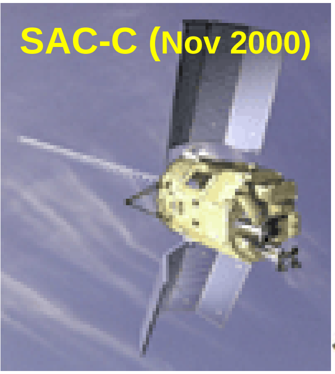
Many national security applications
- **GPS integrity monitoring**
- **GPS enhancements**
- **GPS capabilities to exceed Galileo's**

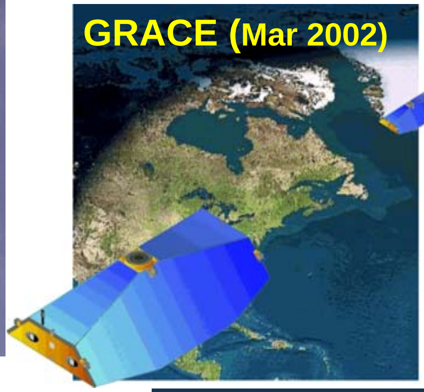
Many commercial applications

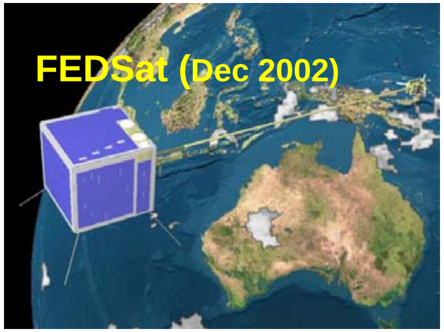
Missions with BlackJack Receivers

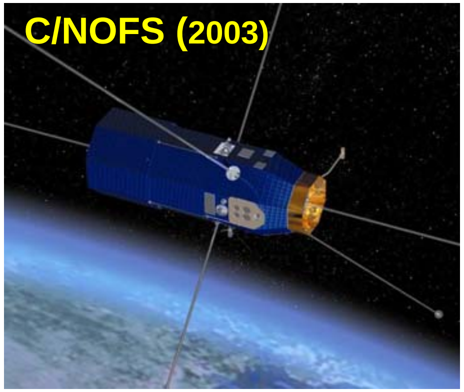
- precise orbit (also on-board, real-time)
- atmospheric remote sensing
- gravity
- ionospheric remote sensing
- ocean surface reflections

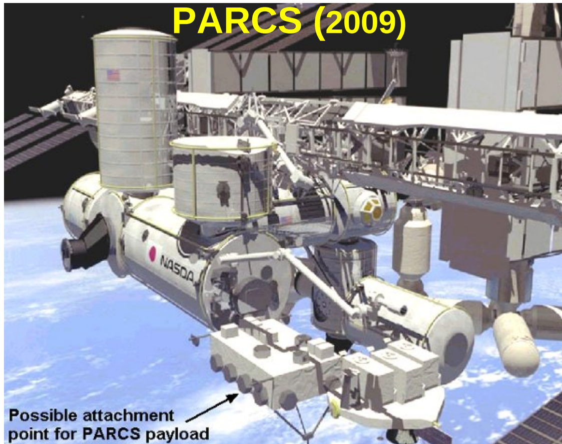






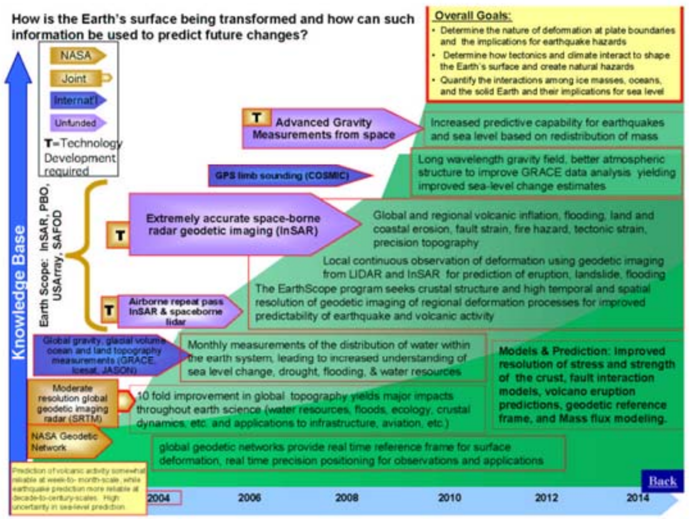


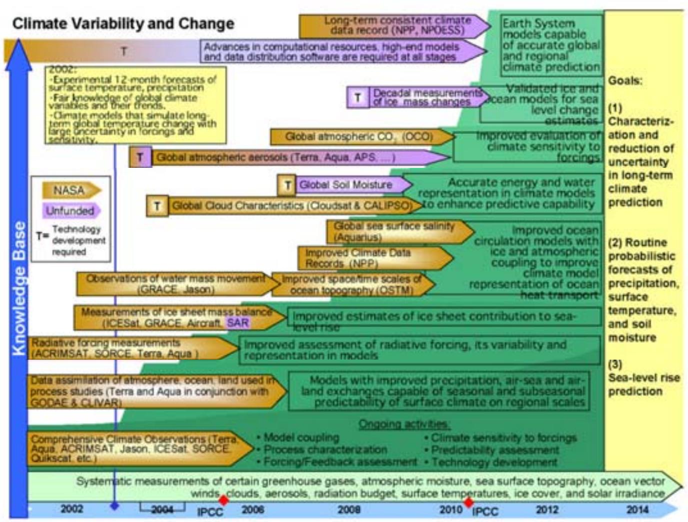




Geodetic Networks:

- A stable and accurate TRF underlies Solid Earth and Climate roadmaps
- SESWG report
  - Geodetic networks are one of seven observation strategies to address the fundamental solid Earth questions.
  - Maintenance of the global geodetic networks, TRF, and Earth Orientation Parameters is the “supporting framework”: an element of the fully realized solid Earth program.

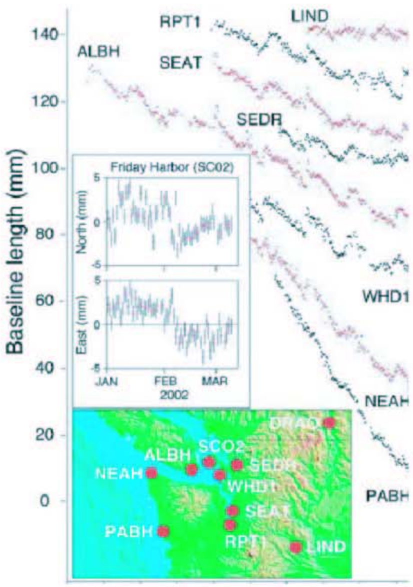




Direct solid Earth science from the ground stations: How is the surface of the Earth changing?

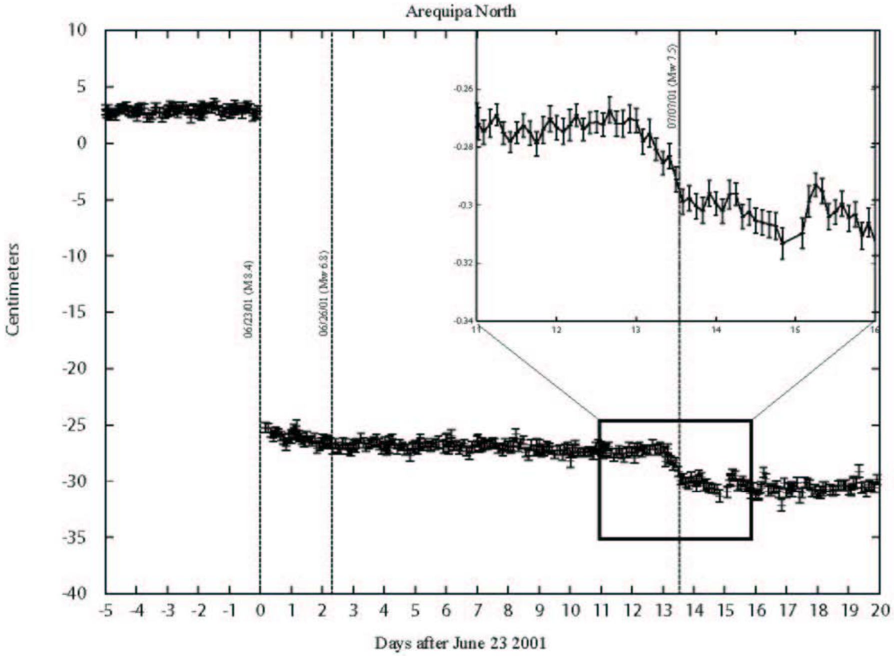
New Discoveries of rarely observed and/or previously unobserved phenomena

Silent Earthquakes



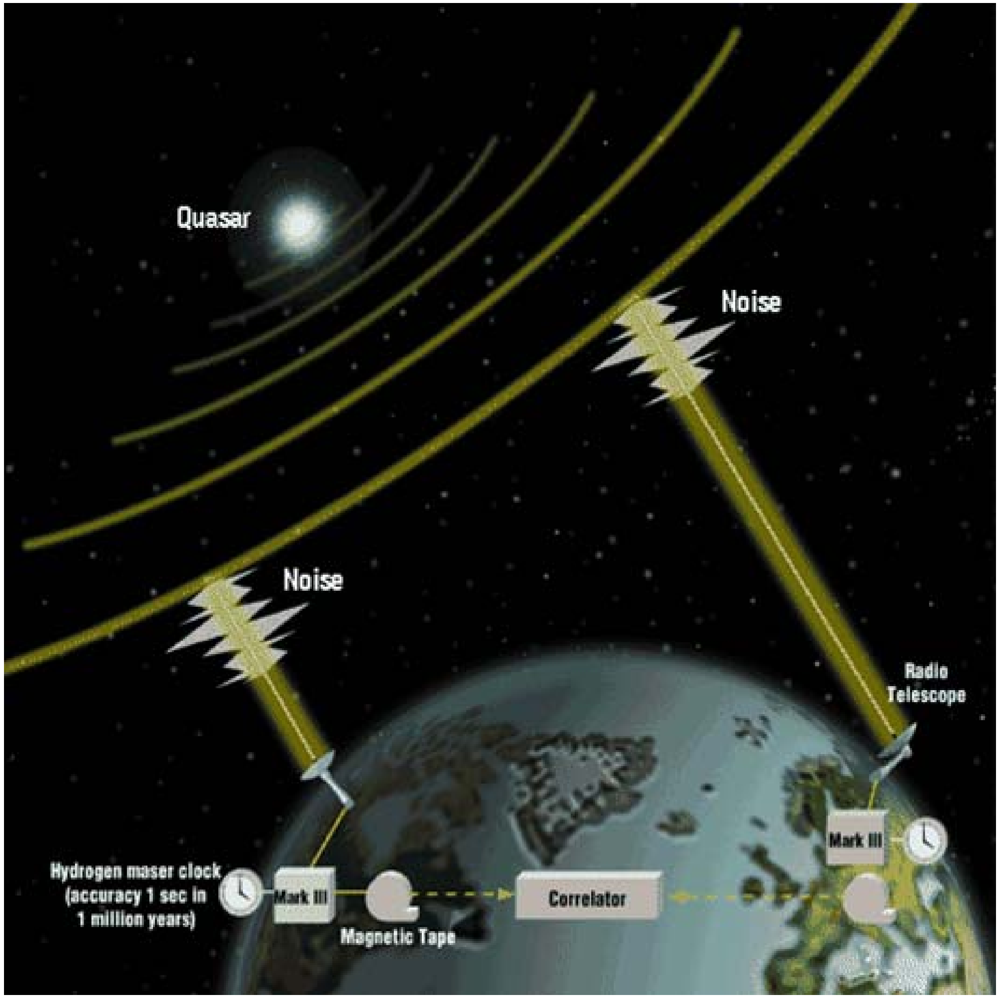
Miller et al, 2002

Seismic precursor

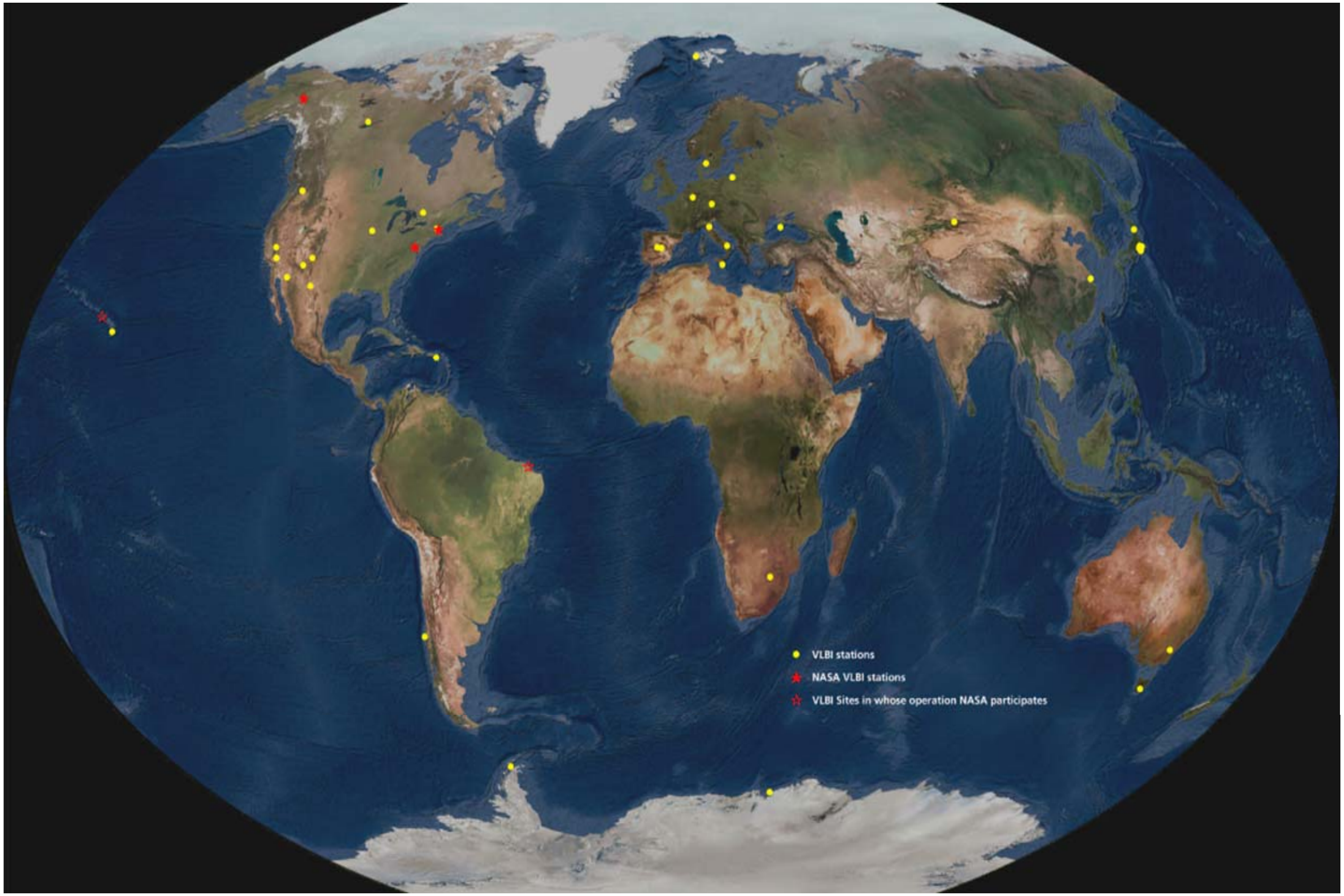


Melbourne and Webb 2002

Geodetic Networks: VLBI

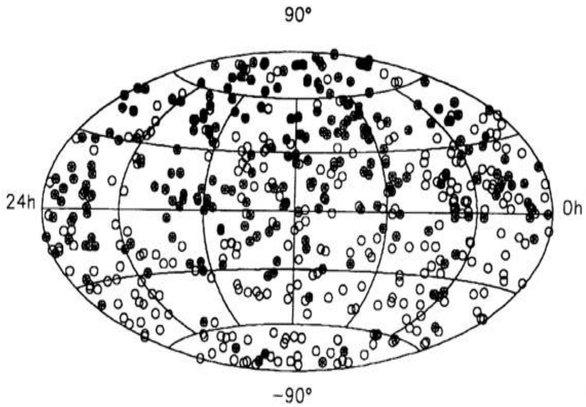


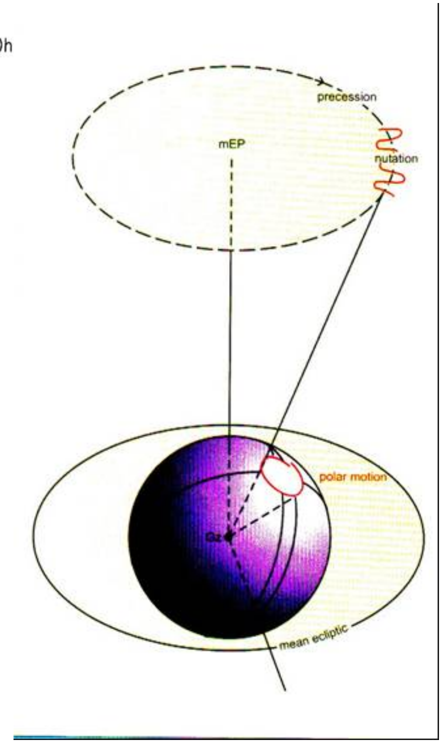
Geodetic Networks: VLBI Station Map



Geodetic Networks: VLBI Unique Capabilities

- Celestial Reference Frame using quasars
- Motion of axis in space
- Earth rotation rate
- Differential navigation for spacecraft





Backup material follows

Geodetic Networks: 5-year outcome

- TRF realized by coordinated multi-technique networks and analysis
  - Sub-centimeter consistency and accuracy globally
  - Improvement in the vertical component
- Consistent and robust access to the improved TRF in real-time for all users
- Improvement in network distributions, characteristics and efficiencies
  - Real-time GPS global sub-network, GNSS, GPS3
  - eVLBI
  - SLR2000
- Analysis development and validation to optimize multi-technique methods
- Improved data and product access interfaces via
  - Proposed collaborative project to implement state-of-the-art services aligned with SEEDS

Geodetic Networks: NASA's role among global collaborators

- Networks, through the TRF, provide critical infrastructure to support flight projects.
  - This support is assumed by current and future missions to be provided yet is rarely budgeted or planned.

- NASA leverages its resources by cooperating with international partners.

  - NASA supports and coordinates the geodetic services through central offices at JPL (IGS) and GSFC (ILRS and IVS).

  - This NASA coordination is a highly successful international activity endorsed by international organizations such as the IAG.

  - NASA's space geodetic data sets are augmented by data contributed by other agencies to the international pool.

  - These activities are supported by the Crustal Dynamics Data Information System (CDDIS), a key data center supporting the IGS, ILRS, IVS, and IERS.

  - This results in access to greater and enhanced data sets and products.

Geodetic Networks: Issues and Challenges

- Maintaining and upgrading aging equipment and hardware
- Transitioning new technology into the definition of the TRF
- Developing new analysis techniques to address evolving requirements and new opportunities
- Identifying a mechanism by which the support for this vital infrastructure can be shared by all users within NASA

Introduction wrap-up

- Geodetic networks support the TRF requirements of NASA ESE missions
- Each of SLR, VLBI, GPS substantially and uniquely contributes to TRF determination
- NASA’s SLR, VLBI, and GPS groups collaborate toward wide-ranging improvements in the next 5 years
- NASA leverages considerable resources through its significant activity in international services
- NASA faces certain challenges in continuing and advancing these activities

Geodetic Networks: GPS Issues and Challenges

Current and pending issues (0-3 years):

- Integration of new techniques, e. g. GALILEO
- Implementation of real-time communications
- New receivers and analysis capability for new signals
- Geophysical model development

Future issues (2-10 years):

- Improved system redundancy
- Verification and validation of TRF stability
- Technology independence of the TRF
- Integrated operation with the other techniques
- Co-location
- Smooth infusion of new technology

NASA ESE Needs for Geodetic Networks

- Long term, systematic measurements of the Earth system require the availability of a terrestrial reference frame (TRF) that is stable over decades and independent of the technology used to define it.

- The space geodetic networks provide the *critical infrastructure* necessary to develop and maintain the TRF and the needed terrestrial and space borne technology to support the Earth Science Enterprise goals and missions.

- This infrastructure is composed of the:
  - Physical networks,
  - Technologies that compose them, and
  - Scientific models and model development that define a TRF.

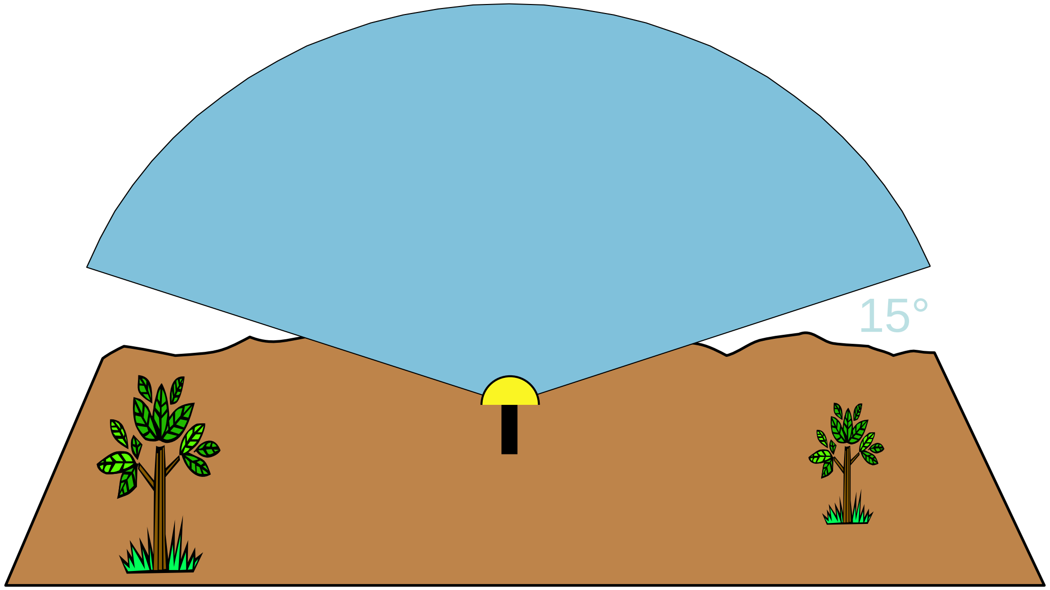
A TRF is a set of positions and a model for how those positions evolve with time

What is Geodetic Scale?

Think of it as the absolute size of the earth:

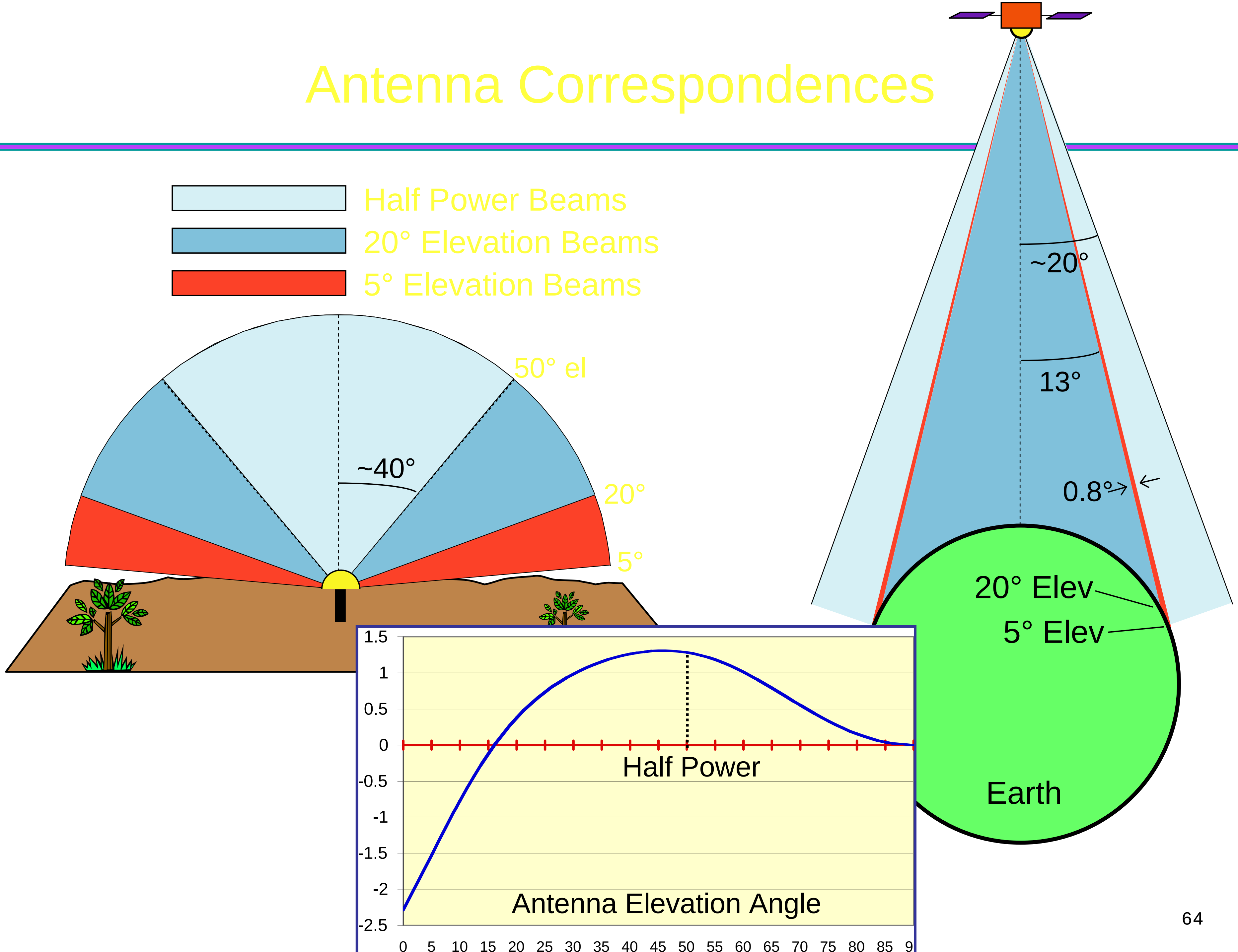
- The true distances between reference points
- The tie of geodesy to our defined distance unit

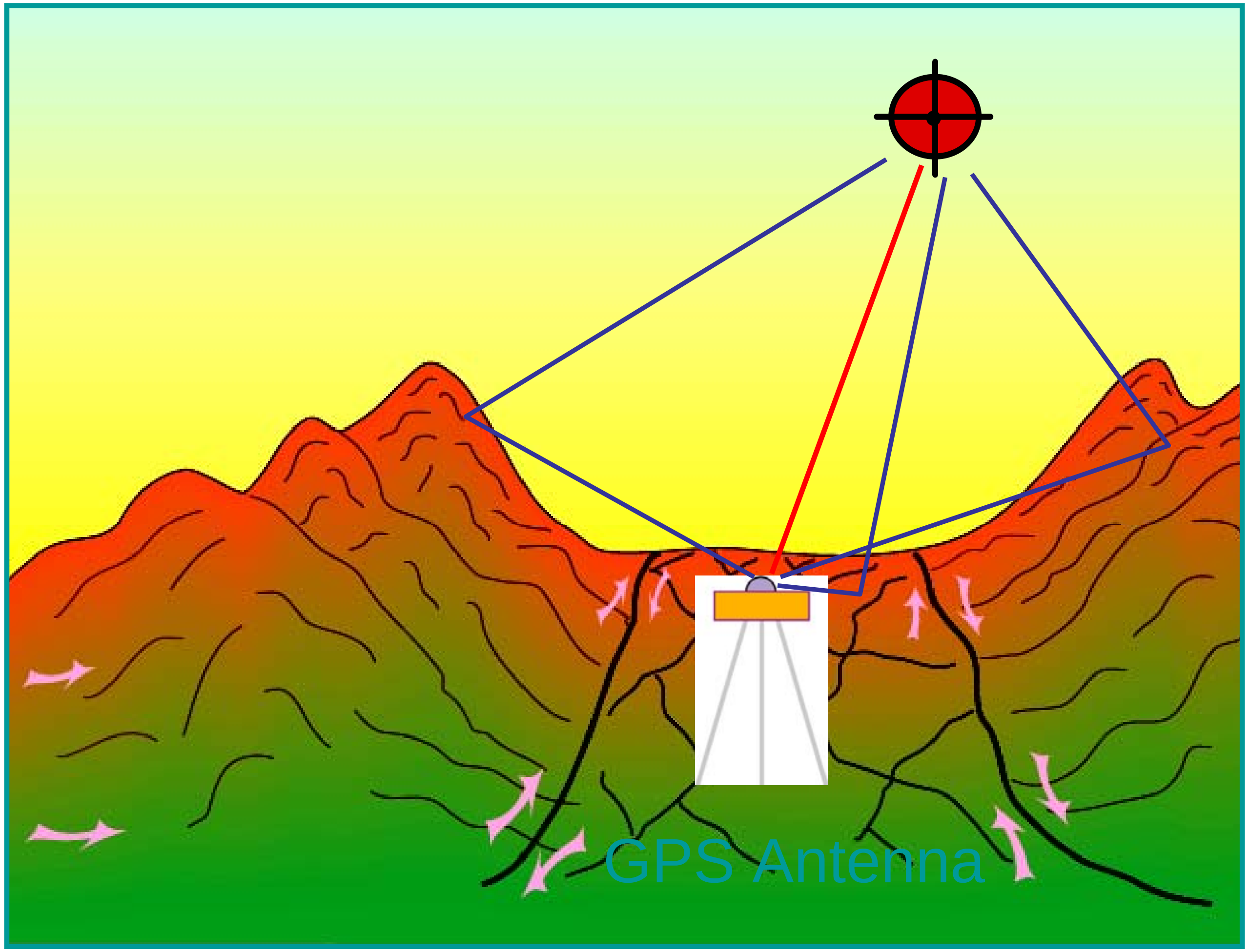
Misconceptions (cont.)



- A 15° elevation cutoff was chosen to yield agreement with IERS scale
- A 15° elevation cutoff was <u>kept</u> to maintain agreement with IERS scale

Antenna Correspondences




GPS Antenna

IGS Product Table

GPS Satellite Ephemerides/Satellite & Station Clocks

[GPS Broadcast values included for comparison]

	ACCURACY	LATENCY	UPDATES	SAMPLE INTERVAL
Broadcast	~260 cm/~7 ns	real time	--	daily
Predicted (Ultra-Rapid)	~25 cm/~5 ns	real time	twice daily	15 min/15 min
Rapid	5 cm/0.2 ns	17 hours	daily	15 min/5 min
Final	<5 cm/0.1 ns	~13 days	weekly	15 min/5 min

GLONASS Satellite Ephemerides

Final	30 cm	~4 weeks	weekly	15 min

Geocentric Coordinates of IGS Tracking Stations (>130 sites)

Final horizontal/vertical positions	weekly	3 mm/6 mm	12 days	weekly
Final horizontal/vertical velocities per year	weekly	2 mm /3 mm	12 days	weekly

Earth Rotation Parameters

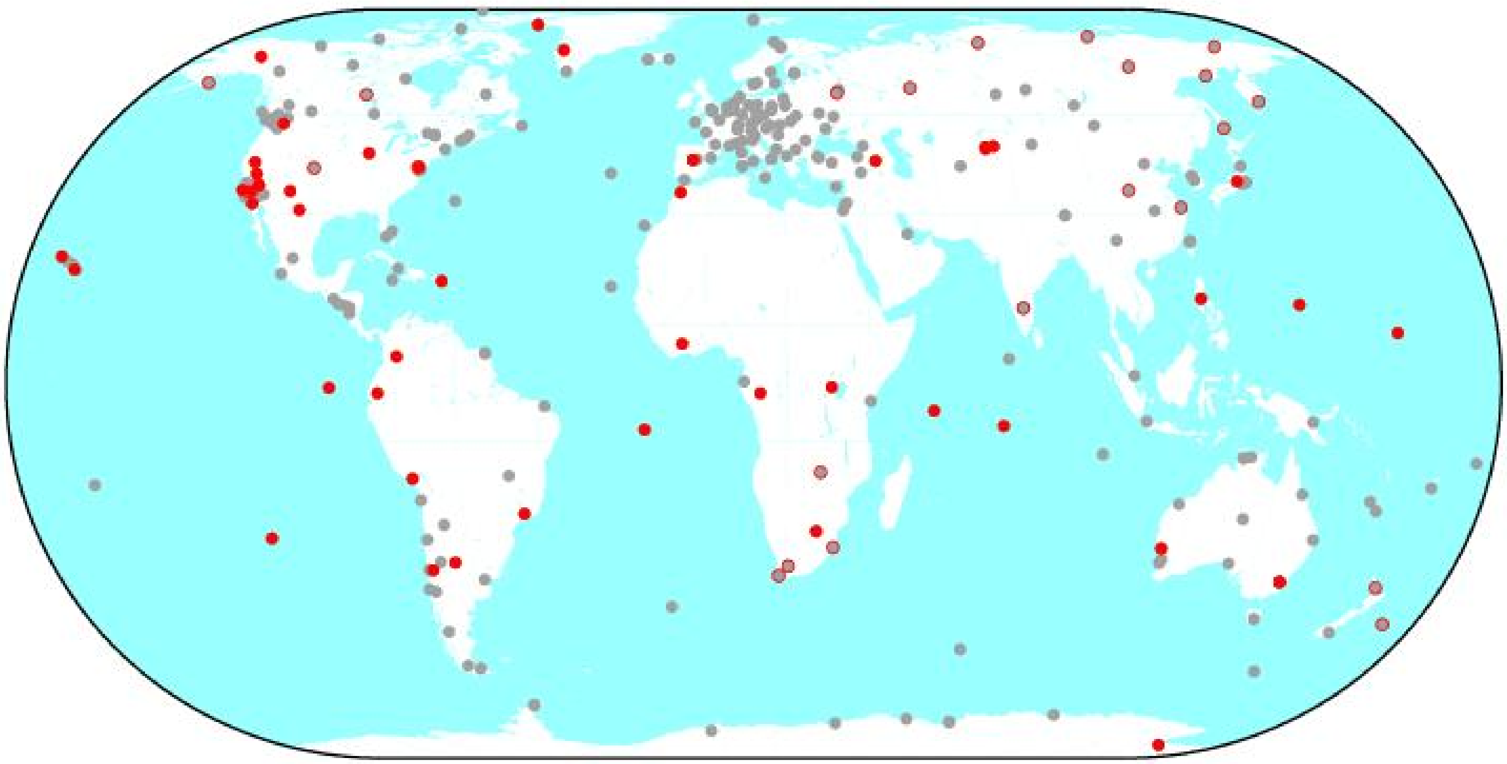
Rapid polar motion/ PM rates per day/ length-of-day	0.2 mas/ 0.4 mas/ 0.030 ms	17 hours	daily	daily
Final polar motion/ PM rates per day/ length-of-day	0.1 mas/ 0.2 mas/ 0.020 ms	~13 days	weekly	daily

Atmospheric Parameters

Final tropospheric	4 mm zenith path delay	< 4 weeks	weekly	2 hours
Ionospheric TEC grid	(under development)			

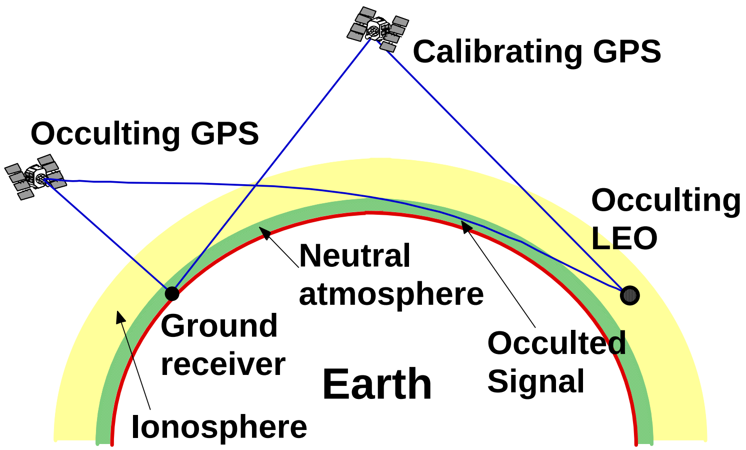
NASA GPS Global Network

Tracking Network of the International GPS Service
Highlighting NASA's Contributions

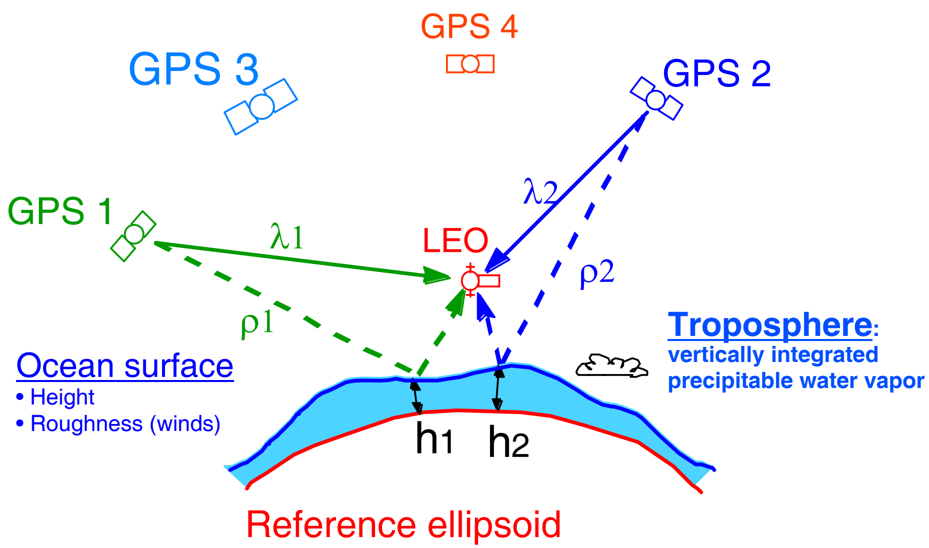


- ● **NASA GPS Stations**
- o **NASA Cooperative Stations**
- ● **Other Agency Stations**

Novel Science Applications

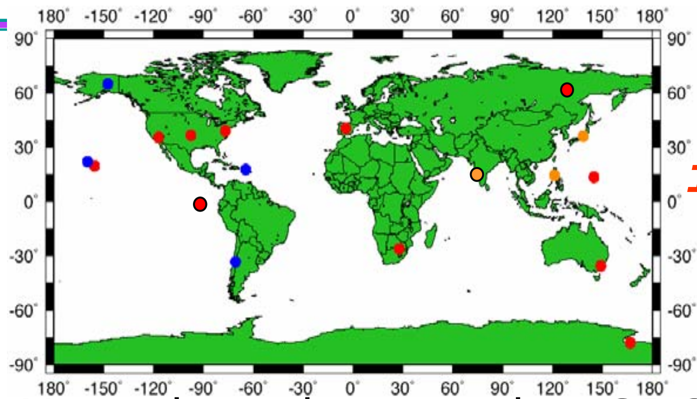


Atmospheric and Ionospheric Remote Sensing and Science



Bi-Static Ocean Reflectometry

JPL's New Global Global Capability Supports 10-20 cm User Accuracy, Anywhere, Real-Time

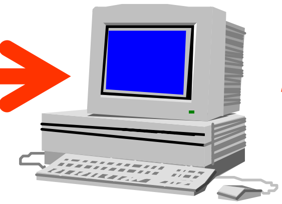


Network receivers running IGDG

Internet

JPL processing center

running Internet-based Global Differential GPS



Broadcast

Internet

Broadcast

Remote user running IGDG

Revolutionary new capability:

decimeter real time positioning, anywhere, anytime

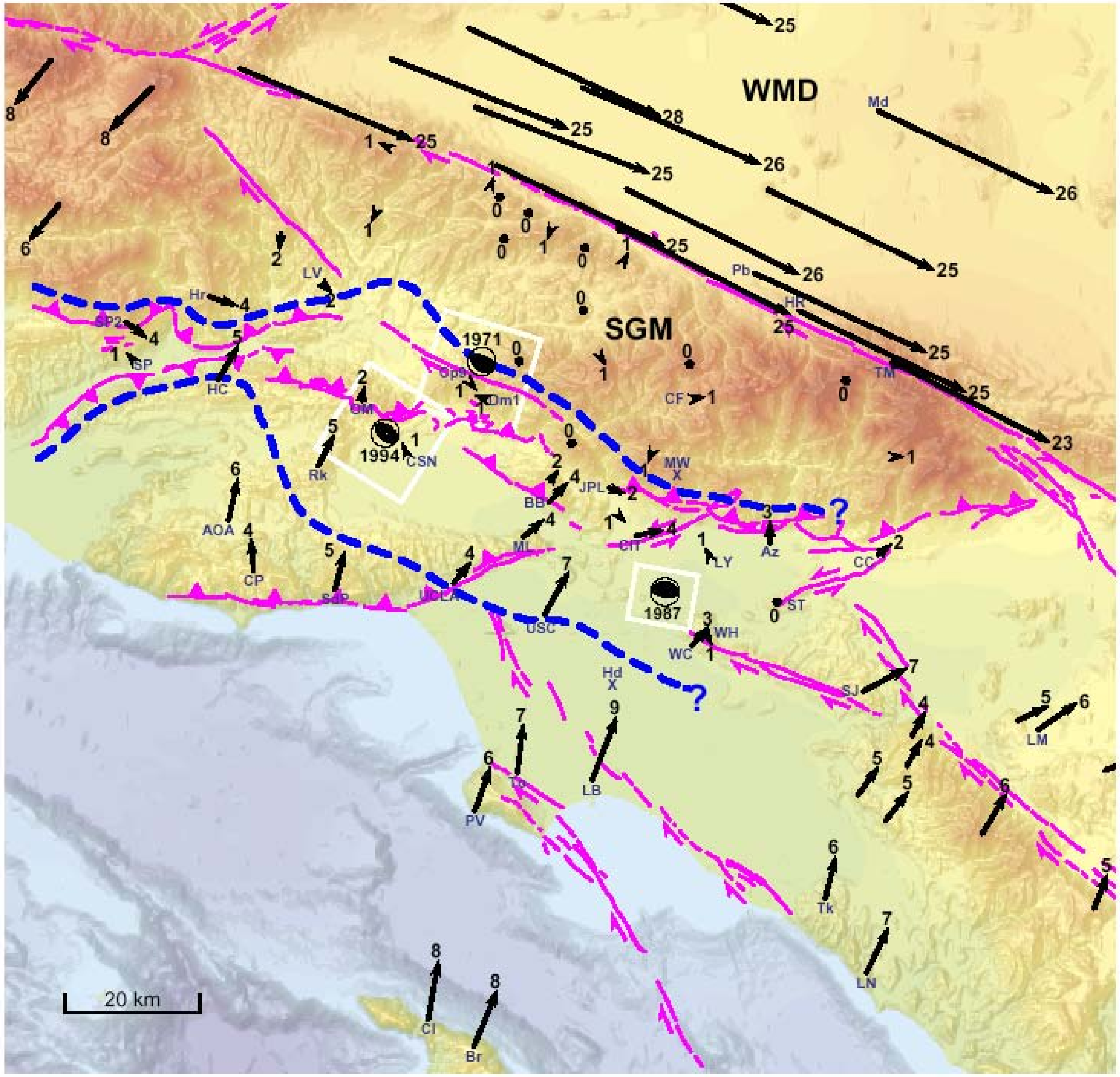
Capability		**JPL's IGDG**	**Un-augmented GPS**	**Others (WADGPS services)**
Coverage:	Global	Yes	Yes	No
	Seamless	Yes	Yes	No
	Usable in space	Yes	Yes	No
Accuracy:	Kinematic applications	0.1 m horizontal 0.2 m vertical	5 m	> 1 m
	Orbit determination	0.01 - 0.05 m (goal)	1 m	N/A
Dissemination method		Internet/broadcast	Broadcast	Broadcast
Targeted users		Dual-frequency	Dual-frequency	Single-freq.

For more info:
http://gipsy.jpl.nasa.gov/igdg

Shortening and Thickening of Metropolitan Los Angeles

residual velocity field

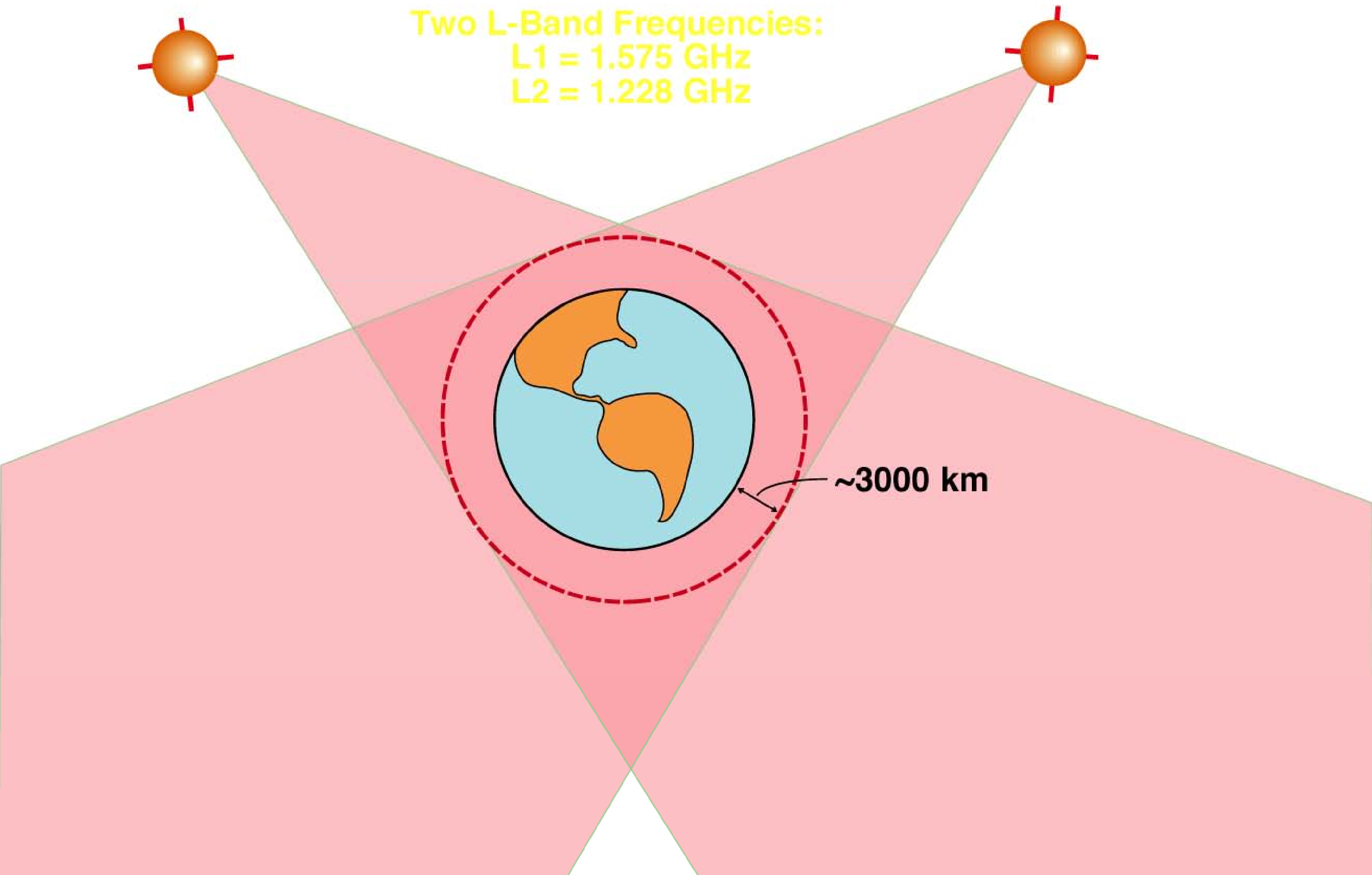
SGM fixed



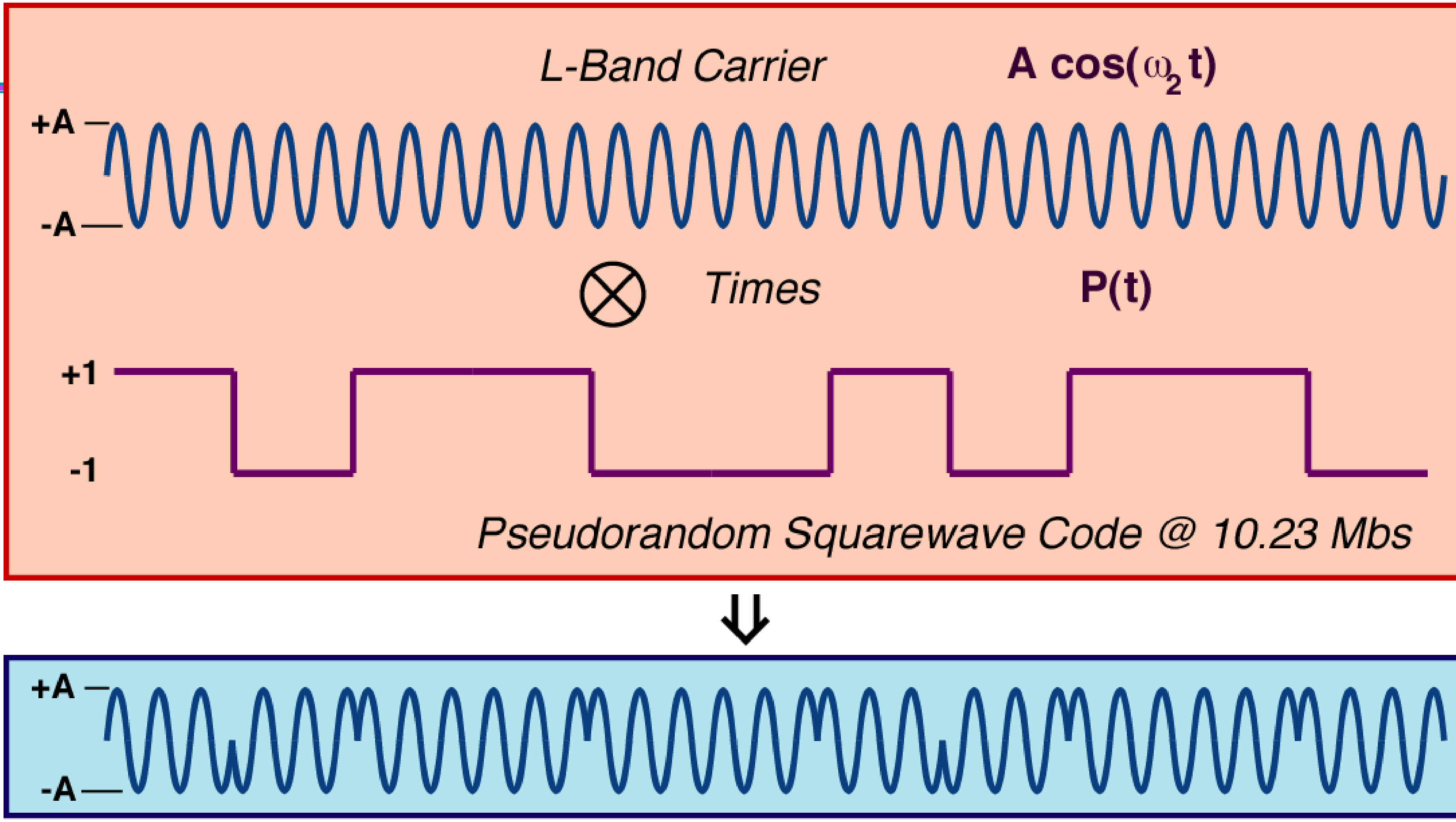
Mojave segment, San Andreas F.

best 25 mm/yr 20 km

GPS SIGNAL COVERAGE



BASIC GPS SIGNAL STRUCTURE

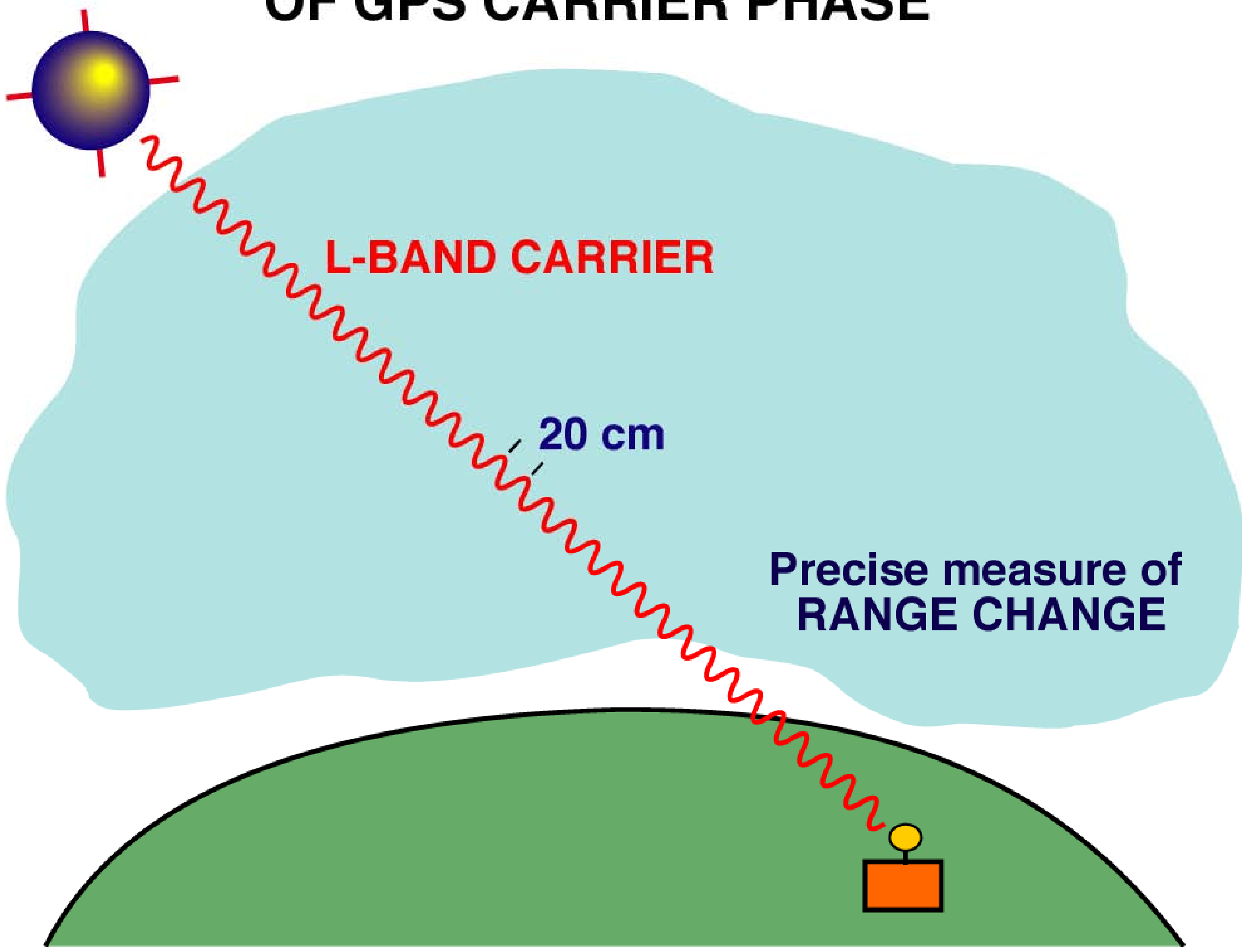


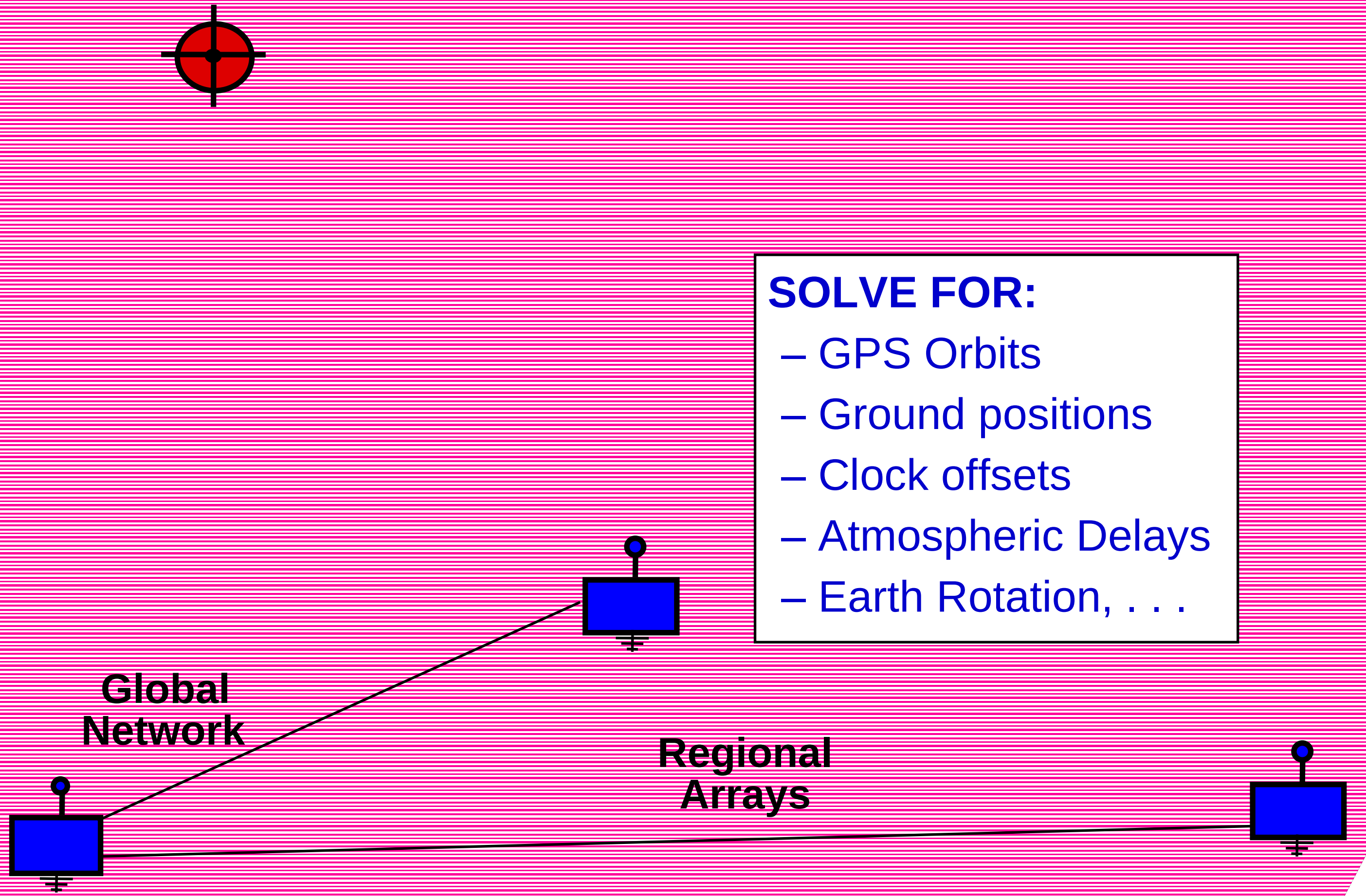
$L2(t) = P(t)\,A\cos(\omega_2 t)$

$L1(t) = P(t)\,B\cos(\omega_1 t) + C(t)\,B'\sin(\omega_1 t)$ *(L1 Carrier = 1.57542 GHz)*

(Pseudorandom Squarewave Code @ 1.023 Mbs)

MILLIMETER-PRECISION MEASUREMENT OF GPS CARRIER PHASE





SOLVE FOR:

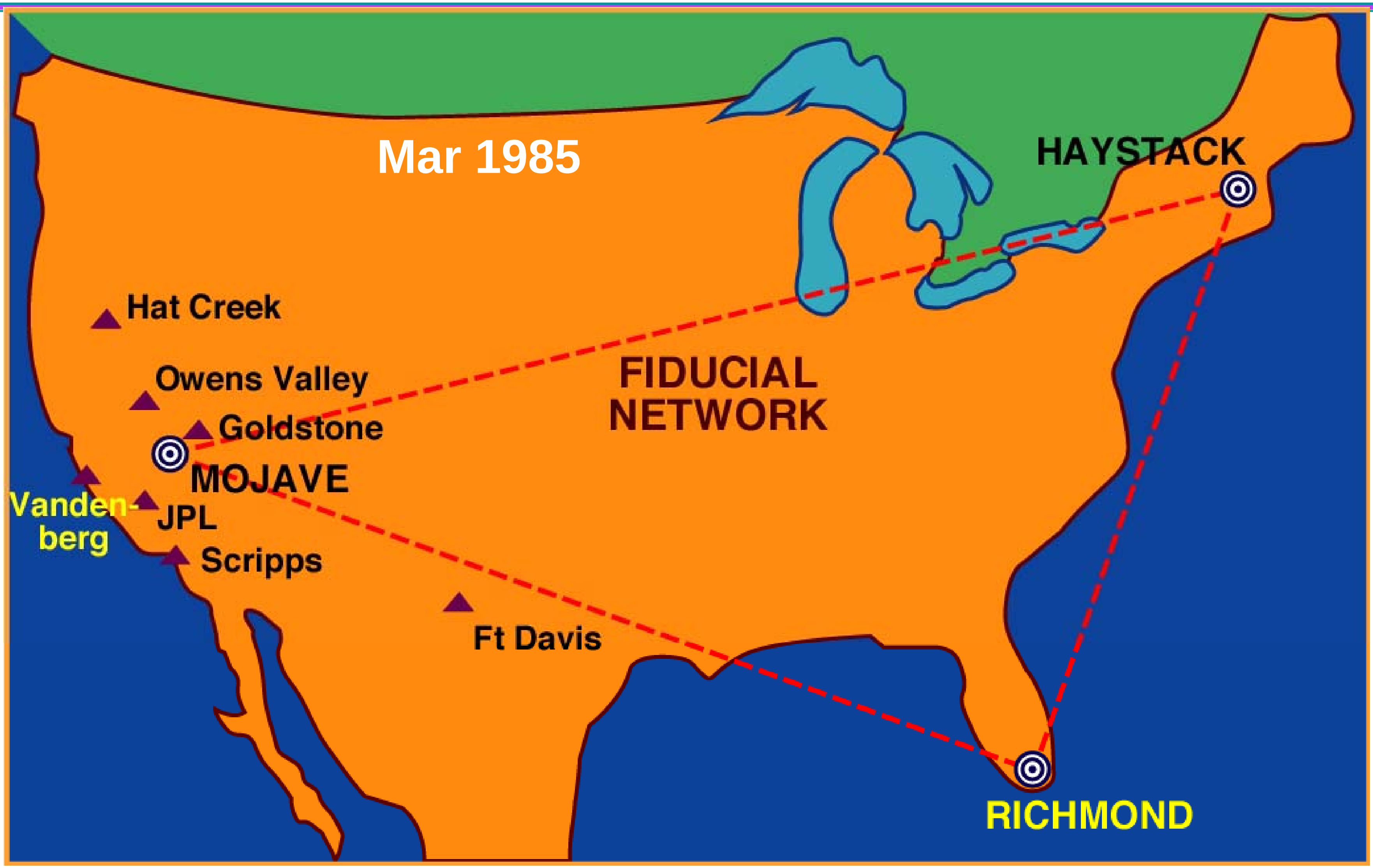
- GPS Orbits
- Ground positions
- Clock offsets
- Atmospheric Delays
- Earth Rotation, . . .

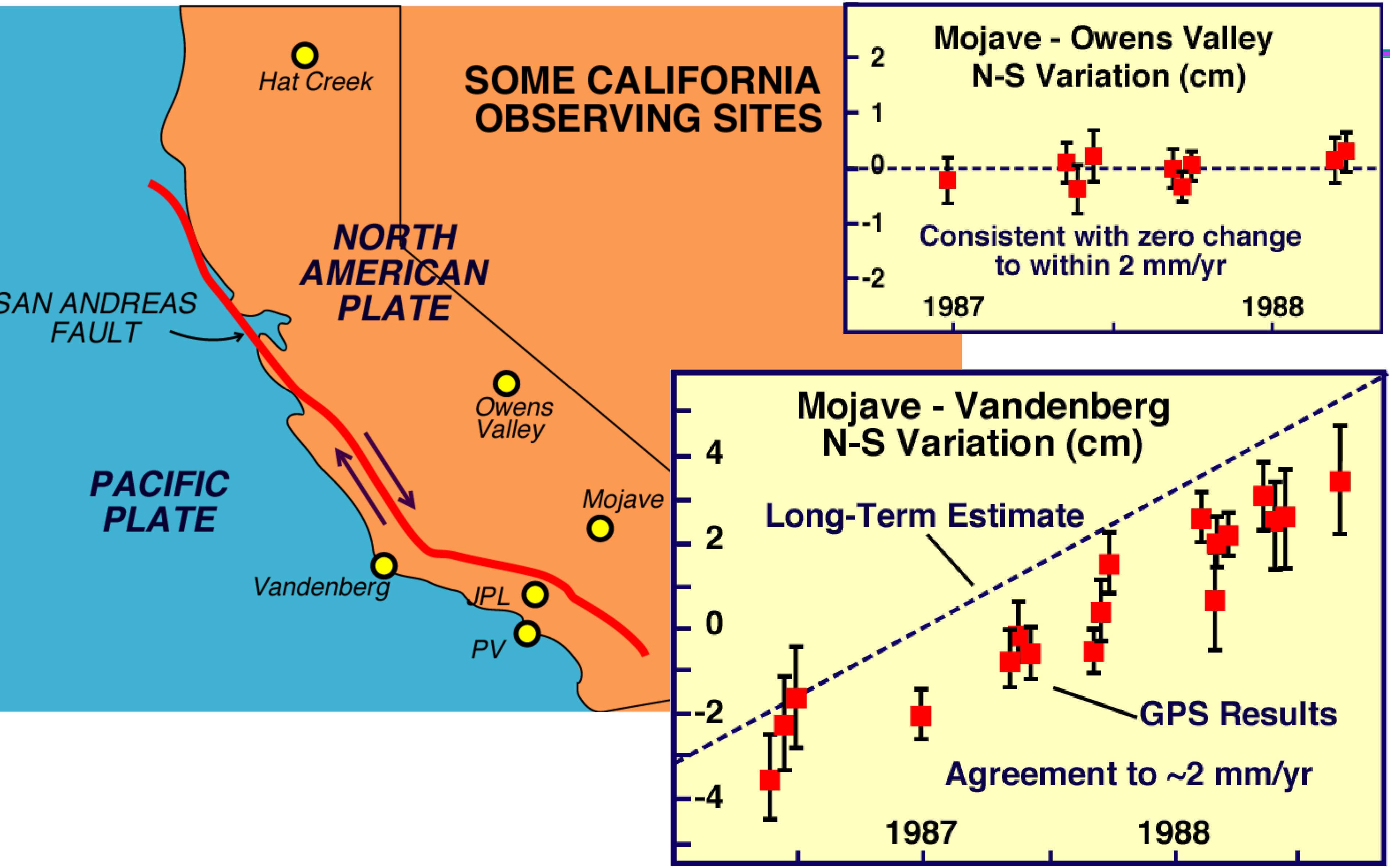
Early Mobile GPS Technology

JPL's SERIES Codeless Receiver c. 1981

(Satellite Emission Radio Interferometric Earth Surveying)

An Early JPL GPS Geodesy Experiment




SOME CALIFORNIA OBSERVING SITES
Hat Creek
NORTH AMERICAN PLATE
SAN ANDREAS FAULT
PACIFIC PLATE
Owens Valley
Mojave
Vandenberg
JPL
PV
Mojave - Owens Valley
N-S Variation (cm)
2
1
0
-1
-2
Consistent with zero change to within 2 mm/yr
1987
1988
Mojave - Vandenberg
N-S Variation (cm)
4
2
0
-2
-4
Long-Term Estimate
GPS Results
Agreement to ~2 mm/yr
1987
1988